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Fuel Tank Technology

NORTH ATLANTIC TREATY ORGANIZATION

DISTRIBUTION AND AVAILABILITY
ON BACK COVER

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.771

FUEL TANK TECHNOLOGY

Papers presented at the 68th Meeting of the Structures and Materials Panel of AGARD in Ottawa, Canada, 23—28 April 1989.

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PREFACE

Aircraft fuel tanks have historically been a source of problems for aircraft designers and users Fuel tank leaks not only cause aircraft to be lost from service, but also result in additional expenses for repairing and returning aircraft to flight status. Flight safety problems related to fuel leaks are a concern.

At the request of Dr James Olsen, then Chief for Research and Technology, Structures Division, US Air Force Flight Dynamics Laboratory, the Structures and Materials Panel was asked to consider the establishment of a Working Committee for Aircraft Fuel Tank Technology. Martin D.Richardson, project engineer in the Structures Test Branch of the Structures Division, volunteered to serve as Technical Advisor to the Working Committee. The objectives of the committee were to exchange experiences and information concerning aircraft fuel tank technology, exchange information concerning current design practices, and discuss current detection, repair and modification practices, including modification to improve tank fuel leak integrity. These goals were to be accomplished through a workshop.

for aircraft fuel tank technology

The Working Committee was established in the Fall of 1987. The Workshop was held during the 68th SMP meeting at Ottawa, Canada, April 23–28, 1989. The Workshop was divided into three sessions, current experience, sealants, and design and certification. Thirteen papers were presented at the workshop and are contained in these proceedings.

The Workshop was very successful in that it provided a forum for the exchange of information in the areas of fuel tank design, repair and test methods. The different approaches to the repair methods was of particular interest to those present. At the conclusion of the third session an open discussion period was held and those present were asked to summarize their conclusions and recommendations.

Clovis L Petrin, Jr
Chairman — Sub Committee on
Aircraft Fuel Tank Technology

* * *

AVANT-PROPOS

Les réservoirs de carburant des aéronefs ont toujours été source de problèmes pour les concepteurs et les utilisateurs d'avions Les fuites des réservoirs de carburant non seulement rendent les avions indisponibles, mais elles entrainent aussi des dépenses additionnelles pour la réparation et la remise en état opérationnel de l'aéronef. Les problèmes de sécurité en vol liés aux fuites des réservoirs de carburant sont également une source de préoccupations.

Suite à la demande formulée par le Dr James Olsen, qui fut à l'époque le Chef de la recherche et de la technologie de la Division Structures du laboratoire de la dynamique du vol de l'US Air Force, le Panel AGARD des structures et materiaux a examiné la possibilité de créer d'un groupe de travail sur la technologie des réservoirs de carburant

M Martin D.Richardson, ingénieur de projet dans la section essais de la Division Structures, a proposé ses services en tant que conseiller technique près du groupe Le groupe de travail avait pour objectif de promouvoir un échange sur l'acquis des connaissances et des informations concernant la technologie des réservoirs de carburant des aéronefs, les dernieres méthodes de conception, et les techniques actuelles de détection de fuites, de réparation et de modification, y compris les modifications destinées à améliorer l'étanchéité des réservoirs de carburant. Ces objectifs devaient etre atteints par le biais d'un atelier organisé sur ce sujet.

Le groupe de travail a été constitué en automne 1987. L'atelier a été organise lors de la 68ème reunion du Panel SMP à Ottawa, au Canada, du 23–28 avril 1989. Les activités de l'atelier se sont déroulées en trois séances, l'état actuel des connaissances, les mastics d'étanchéité, la conception et l'homologation. Les treize communications présentees lors de cet atelier sont incluses dans le présent compte-rendu.

L'atelier a été une réussite en ce sens qu'il a constitué un forum pour l'échange d'informations sur les méthodes pour la conception, la réparation et la vérification des réservoirs de carburant.

Les participants ont été particulièrement intéressés par les différentes approches présentées pour les procédures de réparation La troisième séance s'est terminée par une discussion générale et il a été demandé aux participants de resumer leurs conclusions et recommandations.

Clovis L Petrin, Jr
Chairman — Sub Committee on
Aircraft Fuel Tank Technology

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CONTENTS

INTEGRAL FUEL TANK SEALING PRACTICE AT BRITISH AEROSPACE (KINGSTON)

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SUMMARY

This paper reviews the current integral fuel tank sealing and repair procedures at British Aerospace (Kingston). It describes the materials and processes used in the design and initial manufacture of integral fuel tanks.

The methods used for the repair of leaks in integral fuel tanks are described.

The need to review the current procedures for use on future aircraft using composite materials is highlighted.

1. INTRODUCTION

This paper describes fuel tank sealing practices carried out at the Kingston-upon-Thames factory of British Aerospace. Methods used at other British Aerospace sites are not necessarily the same.

The Harrier was the first Kingston designed in-service aircraft to use integral tanks. Previous aircraft such as the Hunter used flexible bag tanks. Use of flexible bag tanks on the Harrier would have incurred an unacceptable weight penalty and loss of fuel capacity. The Hawk trainer has integral wing tanks.

2. SEALING STANDARDS

In-house sealing standards have been developed to define sealing procedures.

2.1. Fig. 1 shows the initial sealing standard used to seal Harrier GR1/GR3 wing and fuselage tanks.

2.2. Fig. 2 shows the current sealing standard used to seal Hawk wing tanks and Harrier GR5 fuselage tanks.

The aircraft structure is first protected against corrosion by the application of a chromated epoxy primer.

The sealants used are polysulphide sealants. Joints are assembled with interfay sealants, subsequently brush and fillet coats of sealant are applied over the completed joint. A protective barrier coat is applied as the final operation over the GR1/GR3 sealants.

An alternative method of tank sealing is groove/channel sealing. A groove in the mating faces of the peripheral tank structure is sealed using a non-setting fluorosilicone sealant. No BAe Kingston designed aircraft use this sealing method. Though BAe has experience with this sealing system through support of RAF Phantoms and co-production with McDonnell Douglas of the Harrier GR5. The wing, manufactured by McDonnell Douglas, uses groove sealing.

3. DESIGN GUIDELINES

From experience in the design and production of Harrier integral tanks, the following guidelines have been formulated for the design of integral tanks;

(1) Sealing requirements must be taken into account at an early stage of the design.

(2) Tank joints should be designed to minimise the chance of leaks. Sealants should not be used as a gap filler to rectify poorly designed joints or excessive manufacturing tolerances.

(3) Leaks usually start from or are attributable to fasteners. The number of fasteners should be minimised by the use of integrally machined frames and fittings (Fig. 3). Early Harrier aircraft had riveted instead of integrally machined frames. This was due to the limited machining capability available at that time. Later Harriers have integrally machined frames. The reduced number of fasteners gives improved sealing. It also simplifies the sealing process.

Also fasteners should be accessible from both sides. This makes any possible future repairs easier.

(4) Complex joints i.e. multiple overlapping skins should be avoided as they are likely to be difficult to seal.

(5) Avoid the creation of closed structures. The final production sealing operation will be difficult to carry out. Also the tracing and rectification of any in-service leaks will be difficult.

(6) Provide good access to the tank to facilitate the final sealing operation after the tank has been assembled. This will also aid in-service inspection and repair.

(7) The tank structure should be sufficiently stiff to prevent excessive flexing due to flight loads and tank pressure loading. Excessive flexing of the sealing i.e. strains greater than 100-200% will over strain the sealant and increase the chance of leaks. This is important as sealants tend to become less elastic when they age.

(8) The pitching of rivets should be such as to ensure sufficient clamping force on the joint. To obtain this, double rows of rivets are preferred to single rows. Pitching of rivets should be 4 X diameter for skins up to 2.0 mm (0.080 ins) thick and 5-6 X for thicker skins. This may result in closer rivet pitching than is required by stress requirements.

Double pitching of rivets will also greatly reduce excessive straining of the sealants, solid rivets are preferred to blind fasteners where access allows.

Non-expanding shank/non-interference type fasteners have proved difficult to seal.

(9) Of equal importance to the integrity of integral tanks is the quality of the manufacturing operations. Poor manufacturing standards can negate good design practice. Attention should be given to the fit of parts. The sealant should be correctly applied, correct training of the work force is important in this respect.

4. SEALANTS

As has been stated, integral tank design utilises sealants to seal the structure and prevent fuel leakage.

Sealants used for this function require a number of properties which may be summarised as follows:

(a) Fuel resistance.
(b) Resistance to water and microbiological contamination that may occur due to the presence of water in fuel.
(c) Retention of flexibility, tensile strength over the required operating temperature range.
(d) Good adhesion.
(e) Ease of application. The sealants should have a useable work life, minimal shrinkage and room temperature cure. They should meet relevant health and safety requirements.

There are only a limited number of materials which can meet these criteria. The two commercially available materials are polysulphides and fluorocarbon sealants. Polysulphide sealants have a maximum service temperature of 110-120°C. Fluorocarbon sealants have a maximum service temperature of 220-210°C.

(1) Polysulphide Sealants

Polysulphide sealants are available using three different curing agents, dichromate, lead dioxide and manganese dioxide. Each curing agent produces variations in properties. For example, lead dioxide sealants require overcoating with a fuel resistant lacquer for long term fuel resistance. Another variation is in the cure characteristics. Chromate cured sealants generally have a faster cure rate than the equivalent manganese cured sealants.

Ageing of the sealant during storage can also affect the curing rate. Chromate cured sealants appear to cure faster towards the end of their shelf life. Conversely the cure rate of manganese cured sealants becomes slower as they age.

Cure rate is affected by the curing temperature. At temperatures of 10-15°C and below cure rate can become impractically slow. This can cause problems in cold climates, particularly for field repairs. To try and overcome this, repair sealants able to cure at low temperatures have been developed. Cure can also be retarded by low humidity levels.

Lead dioxide cured sealants were the first widely available sealants. The initial sealant used on development Harrier aircraft was lead cured polysulphide overcoated with Buna N. Subsequently the Buna N overcoat was withdrawn from manufacture. It was replaced with a nitrile/phenolic overcoat. Later marks of Harrier and Hawk aircraft are sealed with dichromate cured sealant. These have the advantage that they do not require overcoating, to obtain maximum fuel resistance.

Lead dioxide cured sealants are little used today. Dichromate cured sealants followed by manganese cured are the commonly used sealants.

(2) Fluorocarbon Sealants

These sealants were developed as high temperature sealants. However they are considerably more difficult to handle and apply than polysulphide sealants. There is a high solvent content which results in a large shrinkage on curing. Hence they are normally only used where their high temperature capability is essential. They have not been used on BAe Kingston designed aircraft.

For any of the sealants, it is important that they are not allowed to completely dry out when the aircraft is defuelled. If the sealants do dry out shrinkage and cracking can occur.

<u>Channel Sealants</u>

For groove/channel sealing non-setting fluorosilicone sealants are used. These are usually modified with a microsphere filler to alter the flow characteristics.

5. REPAIR OF FUEL TANK LEAKS

Fuel tank leaks may occur due to a number of different causes;

(1) Excessive flexing of the tank structure causing overstraining and cracking of the sealant.

(2) Accidental damage, bird strikes etc.

(3) Sealant ageing

Fuel leaks may also occur during initial manufacture. This has been found to be commonly caused by an incorrectly set rivet.

Successful repair of tank leaks depends on the application of the following criteria:

(a) Tracing the exact source of the leak. There are several methods which can be used for leak tracing. In initial build proprietary leak detecting fluid and french chalk may be used.

In service aircraft often pose problems with access. For use on Harrier aircraft a system of applying a vacuum to the tank has been devised (Fig. 4). The access door on the tank is replaced with a transparent acrylic window. The tank is filled with fuel and a vacuum applied. The source of the leak is indicated by the air bubbles drawn into the tank.

It should be noted that the entry and exit points of the leak may be widely separated.

(b) Selection of the appropriate repair method.

(c) Careful cleaning and surface preparation.

(d) Selection of the correct repair sealant.

(e) Correct preparation and application of the sealant.

(f) The sealant must be correctly cured before subsequent use.

Access is often a major problem in carrying out repairs. To improve access on early Harrier GR1/GR3 wings extra access holes were added by repair action. These have now been incorporated as original build on later production wings.

Slushing has been investigated as an alternative method of repair. Trials were carried out with limited success. Problems were encountered with excessive build up of sealant due to trapping of the sealant in difficult to drain areas. Trials with a solvent drying nitrile lacquer also showed up problems with cure of the sealant in thick sections. Cure was incomplete, also entrapment of air occurred.

6. CONCLUSION

The methods, materials and procedures of integrally sealed metal aircraft tanks are now well defined. Certain improvements to materials, such as tolerance to poor surface preparation and quicker cure would be of additional benefit.

The introduction into service of large scale carbon fibre structures necessitates a re-appraisal of sealing procedures. The suitability of sealing methods optimised for metal structures needs to be reviewed to see if they are appropriate for sealing composite structures. The ability of composites to manufacture shapes not previously possible with metal may require new sealing procedures.

Fig.1

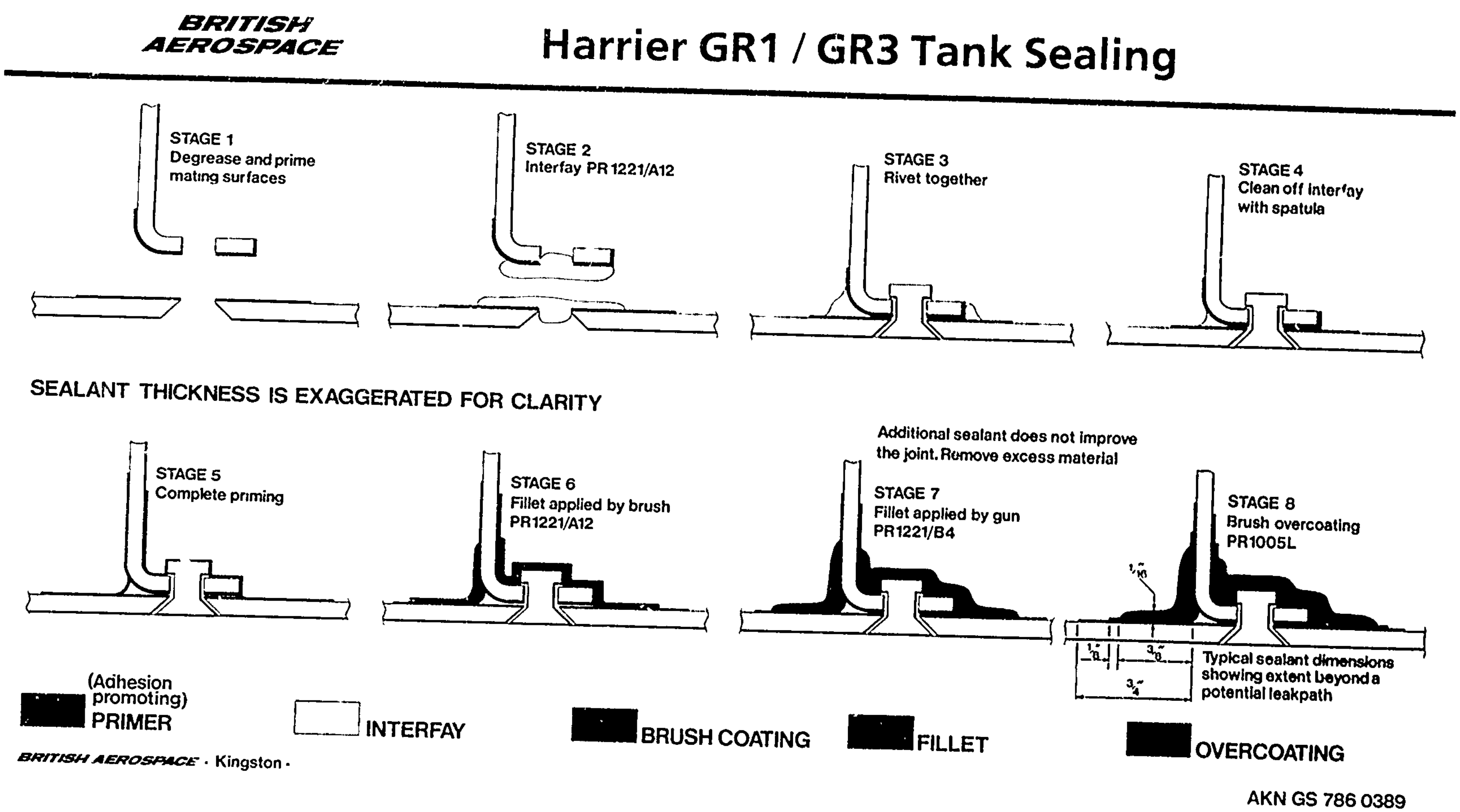
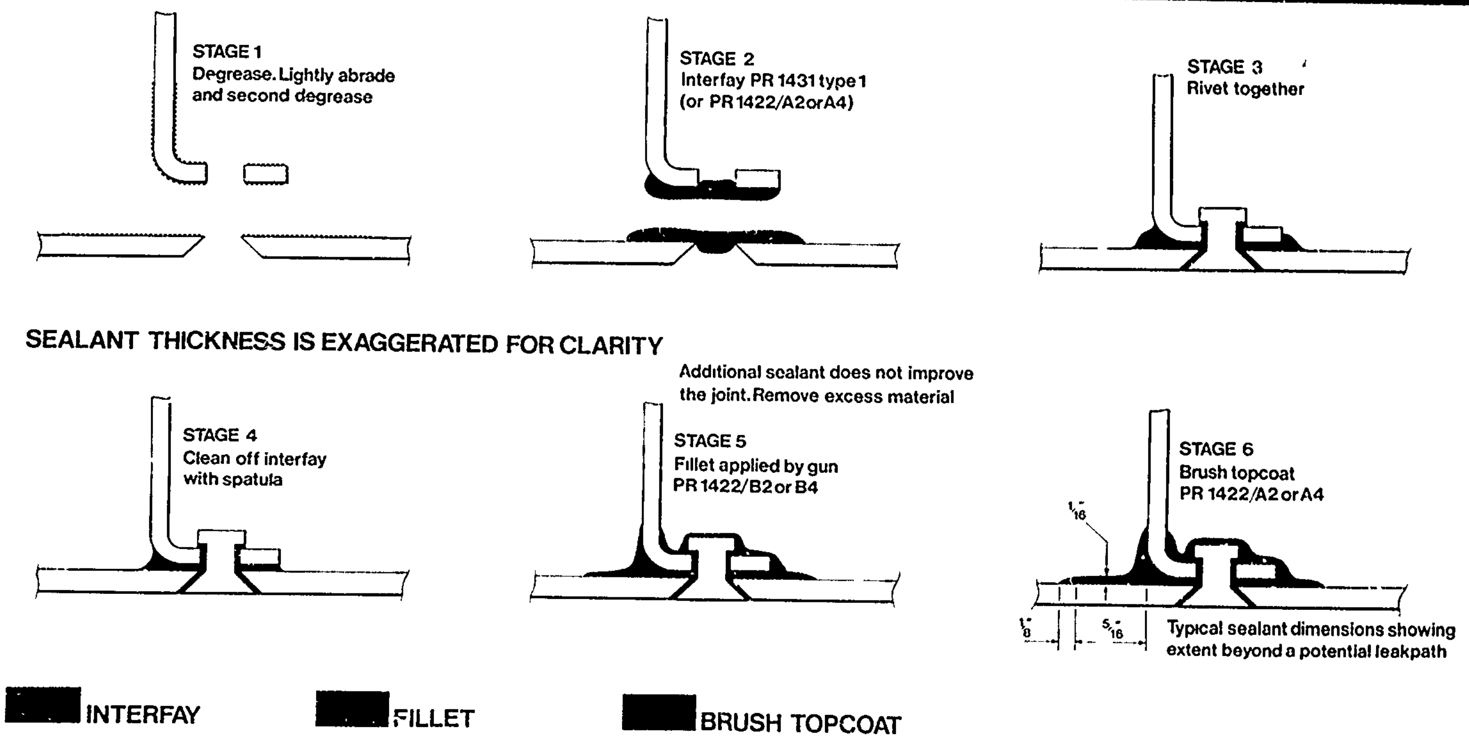

BRITISH AEROSPACE
Harrier GR1 / GR3 Tank Sealing
STAGE 1
Degrease and prime mating surfaces
STAGE 2
Interfay PR 1221/A12
STAGE 3
Rivet together
STAGE 4
Clean off interfay with spatula
SEALANT THICKNESS IS EXAGGERATED FOR CLARITY
STAGE 5
Complete priming
STAGE 6
Fillet applied by brush PR1221/A12
Additional sealant does not improve the joint. Remove excess material
STAGE 7
Fillet applied by gun PR1221/B4
STAGE 8
Brush overcoating PR1005L
Typical sealant dimensions showing extent beyond a potential leakpath
(Adhesion promoting) PRIMER
INTERFAY
BRUSH COATING
FILLET
OVERCOATING
BRITISH AEROSPACE · Kingston ·
AKN GS 786 0389

Fig.2

BRITISH AEROSPACE

Harrier AV-8B and MK5 Tank Sealing



BRITISH AEROSPACE · Kingston ·

AKN GS 785 0389

Fig.3

BRITISH AEROSPACE

Harrier Tank Structure Joints

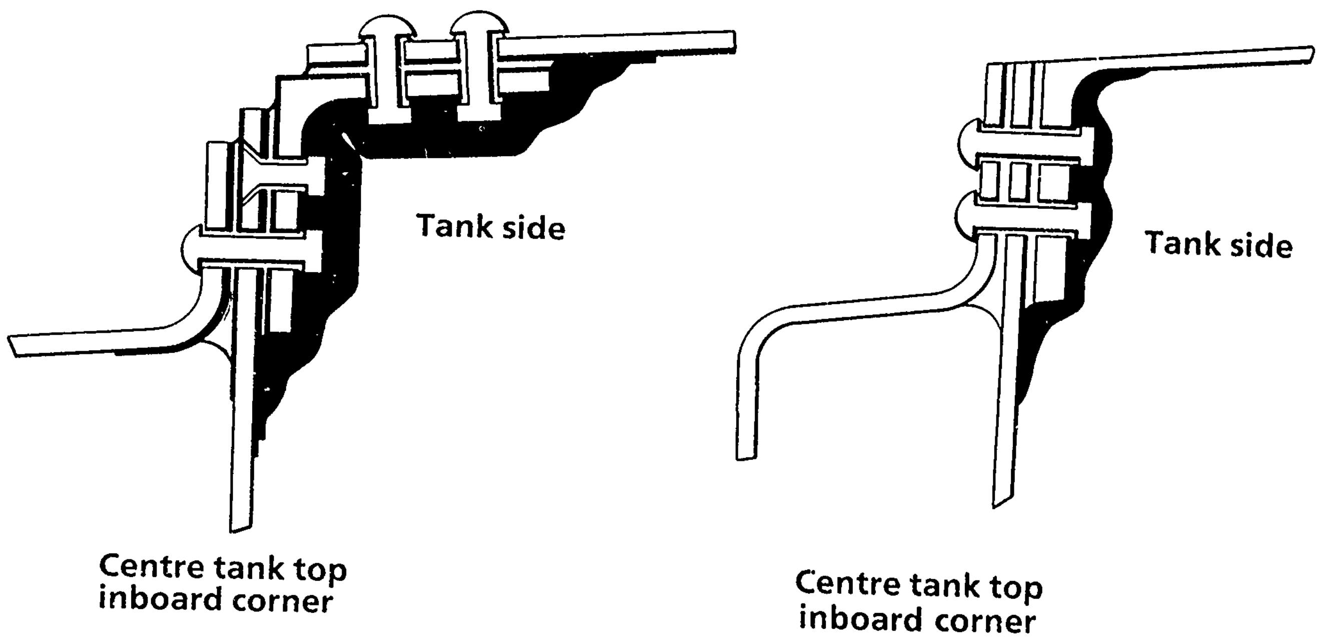


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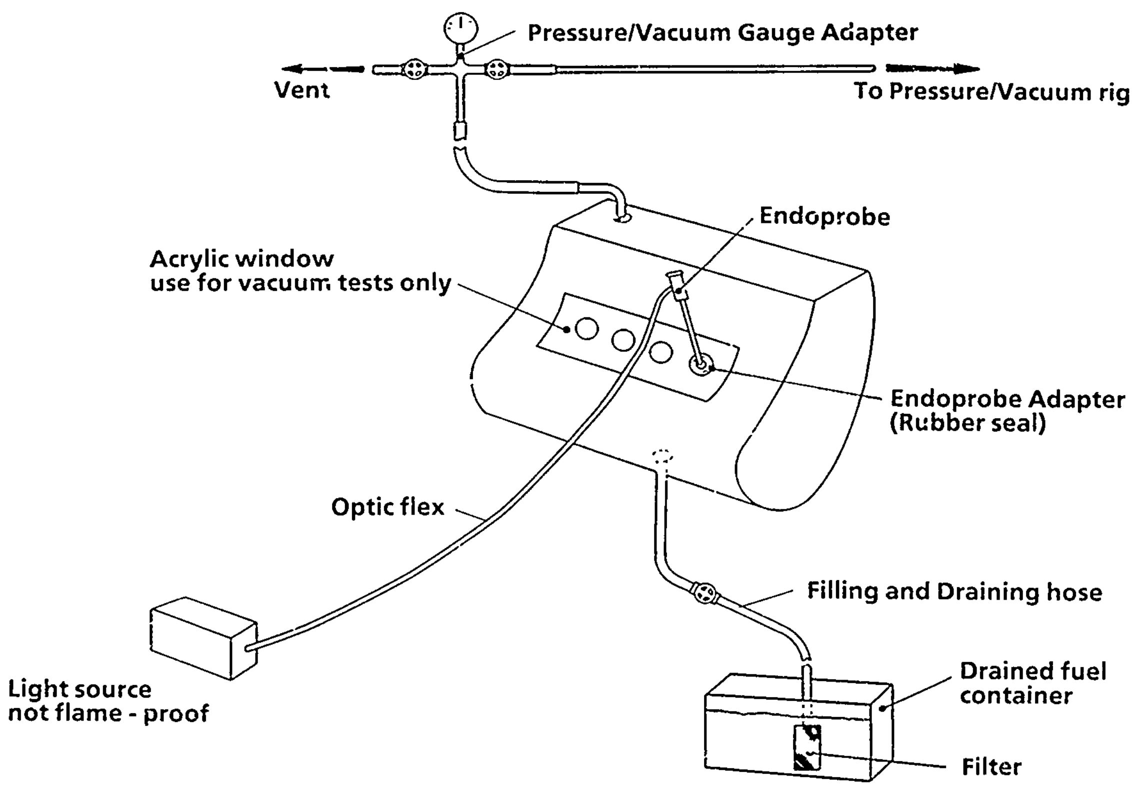
Fig.4

BRITISH AEROSPACE

Leak Detection



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LES RESERVOIRS DE CARBURANT STRUCTURAUX
CONCEPTION, REALISATION, VIEILLISSEMENT, REPARATION

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1 - INTRODUCTION

Les premiers réservoirs de carburant ont été réalisés par des caissons métalliques étanches fixés en partie haute de la cellule qui alimentaient les moteurs par gravité. Une amélioration majeure a été faite par l'emploi de réservoirs souples logés en cellule dans les places laissées disponibles par la structure et les aménagements, le transfert du carburant se faisant alors par pressurisation. Cette solution a permis d'augmenter considérablement le volume potentiel des réservoirs. Les désavantages majeurs se sont révélés être le poids et la complexité d'installation et de maintenance. L'introduction de la structure intégrale pour la réalisation de cellule métallique a permis par étanchement des caisssons intégrés de gagner du poids et des capacités internes considérables et d'assurer une solution moderne au problème des réservoirs.

2 - LES RESERVOIRS SOUPLES

Dans notre société, cette solution a été employé largement en particulier sur les avions d'armes, un exemple est donné par le SMB2 chasseur monomoteur supersonique des années 60.

Ces réservoirs souples en élastomère armés d'une toile résistante présentent l'intérêt de pouvoir être installés postérieurement à la fabrication de la cellule avion, celle-ci est prévue en conception pour admettre des démontages et une accessibilité aux intercommunications et aux fixations. L'installation et les essais de réservoirs sont donc faits en fin de chaîne de production.

De plus, pour les avions militaires, l'utilisation de parois self-obturante par des enductions extérieures permet d'assurer une survivabilité aux dommages de combats.

Les inconvénients de la solution sont :

- le poids de l'installation,
- la fragilité des parois et des attaches de montage en structure et d'intercommunication entre réservoirs, la sensibilité du matériau aux grandes différences de température, en particulier au froid (-50°C),
- la sensibilité à la qualité d'installation, plis, surtension, fixations.
- les difficultés pratiques d'accès et de remplacement,
- la péremption des réservoirs eux-mêmes.

Au cours du temps, des améliorations ont été apportées :

- Des allègements considérables ont été obtenus par l'emploi de paroi très fine (0,6 mm), grâce à des matériaux très résistants enduit de résine synthétique (Polyesther/Nitrile).
- Amélioration des techniques de collage et de liaison des renforts locaux au droit des introductions d'efforts concentrés sur les réservoirs eux mêmes.
- Amélioration sur la conception de l'ensemble de la quincaillerie.
- L'amélioration de la tenue au froid des enductions.
- Une amélioration de la conception des enceintes recevant les outres. En effet, pour éviter la création de plis ou de surtension des réservoirs lors de leur de leur mise sous pression, on a prévu en structure des garnitures de produit en mousse rigide (Klégecel) pour assurer une assise continue de la paroi support de réservoir (Raidisseurs revêtus, marches d'escalier à angle adoucis, etc..).
- Notons que par sécurité certains réservoirs sensibles type nourrice ont été conservés en caisson alliage léger soudé.

L'exemple de ce type d'installation est donné par l'avion SMB2 (figure 1) dont la configuration est la suivante : il comporte 2 réservoirs de fuselage, 2 réservoirs de plan central "Superflexit", un réservoir de soute en tôles d'alliages légers soudés, chaque demi-voilure est équipée de dix réservoirs souples (MARSTON) (figures 2 et 3).

3 - LES RESERVOIRS STRUCTURAUX.

Des progrès notables ont été fait dans la conception de structure avion, en particulier pour les voilures par adoption des revêtements à raidissage intégral. Les panneaux de voilure sont usinés dans une tôle épaisse pour obtenir une tôle de fond à la forme aérodynamique, équipée du côté interne d'un réseau de raidisseurs intégrés.

Le montage général du caisson de la voilure se fait en suivant des méthodes précises d'étanchement. Le volume interne constitue le réservoir de carburant.

Les avantages résident dans l'allègement par élimination des outres et des garnitures Klégecell et dans la simplification des intercommunications. De plus, les volumes à carburant peuvent être de forme quelconque pourvu qu'on ait prévu en gamme la méthode d'étanchement.

Il a fallu cependant trouver les produits de scellement ayant les qualités requises.

Un exemple de ce type de voilure étanche et donné par le MIRAGE III (figure 4).

. Cet avion possède 2 réservoirs structuraux occupant le volume du caisson principal de voilure, et deux réservoirs de bord d'attaque. Le fuselage comporte 4 réservoirs souples et deux nourrices, occupant le volume libre entre la manche à air central et le revêtement.

. La solution intégrale a été généralisée sur le fuselage de l'avion MIRAGE F1 et sur le MIRAGE 2000 (figure 5).

Le carburant est entièrement contenu dans les réservoirs structuraux internes soit : 2 nourrices symétriques, un réservoir central avant, 2 réservoirs latéraux et un réservoir central.

4 - ETANCHEITE DES RESERVOIRS STRUCTURAUX

4.1 - Généralités.

La réalisation d'une étanchéité structurale répond à des impératifs qui confirment et complètent les règles de dessin de structure. Pour une bonne efficacité, l'étanchéité doit être prévue dès la conception de la structure.

Les deux grands problèmes sont étanchement des liaisons d'éléments de parois (revêtement, lisse, cadres, porte, renforts) et l'étanchement des fixations elles-mêmes.

L'étanchement général s'obtient par emploi :
- de joints qui assurent la continuité de frontières entre les différents élements.
- d'enduction spécifique pour étancher les fixations.

4.2 - Principes.

Après étude et expérience, il a été établi quelques principes pour assurer l'étanchéité et assurer sa bonne conservation :

1 - Le joint d'étanchéité doit être continu et fermé sur lui même.
2 - Un joint non réparable doit être doublé par un second dit de "sécurité" (réparable ou non) - exemple : interposition entre les surfaces de contact et cordon de PR bordure sur la périphérie et revêtement de voilure.
3 - Un joint réparable n'est pas doublé d'une "sécurité", sauf s'il y a danger en cas de fuite (incendie, court-circuit).
4 - Le joint sera aussi homogène que possible de nature et de section.

4.3 - Produits utilisés.

Après de nombreuses études, les produits les plus performants se sont révélés être les polysulfures sous différentes formes vulcanisant in situ par réaction de polymérisation sous l'action d'un accélérateur.

Qualités des produits.
- Une bonne cohésion après complète polymérisation.
- Une bonne élasticité.
- Une bonne adhérence sur les matériaux structuraux usuels convenablement préparés.
- Une bonne longévité en présence de carburant et d'humidité.
- Une tenue mécanique convenable pour les températures usuelles des réservoirs avion (- 50 à + 100°).
- Une grande stabilité chimique dans les conditions normales d'utilisation (décenie).
- Une mise en place relativement aisée dans les limites du temps de travail.
- Une très bonne réparabilité après les préparations d'usage.

Inconvénients.
- Le mélange des composants doit être soigneux, le "débullage" en est malaisé.
- Mauvaise adhérence sur une surface mal préparée (propreté).
- Temps de travail trop court pour un temps de polymérisation trop long.
- Problèmes de thixotropie.

Les produits sont différents dans leur présentation suivant leur usage :
. Produits fluides type A pour les couches d'assises et de recouvrement.
. Produits thixotropes type B pour les cordons d'angle.
. Produits de protection type vernis employés en remplissage vidange.
. Produits de protection antibactérienne.

4.4 - Les joints.

Les joints peuvent être classés en deux grands groupes :

4.4.1 - Joints apparents (figure 6).

- Cordon d'angle.

Ces cordons très sûrs, peuvent être placés à l'intérieur ou à l'extérieur du caisson. Ils sont constitués par :
. 1 couche d'assise
. 1 cordon épais
. 2 couches de recouvrement.

- Cordons "inter-tôle".
Très fréquents en bordure de panneaux intégraux. Ils sont constitués d'une ou deux couches de "PR".

4.4.2 - Joints non apparents (figure 7).

Pratiquement, ils ne sont pas réparables ; par suite, ils sont doublés par une "sécurité".

· Cordons injectés.

Ce sont des cordons logés dans une gorge prévue à cet effet et situés à la frontière de deux éléments assemblés. Cette gorge, usinée dans l'épaisseur du panneau ou des semelles de la sous structure, ne doit pas amener de faiblesse mécanique des éléments ni de problèmes de fatigue d'où certains profils de la section.

- Joint d'interposition.

Exécuté avec du produit à prise lente, une couche mince de produit est écrasée au montage dans l'empilage des tôles. Son épaisseur est d'environ 5/100ème.

L'accostage définitif des éléments doit impérativement être terminé dans le temps de travail du produit.

4.5 - Etanchéité des fixations.

L'étanchéité des fixations obéit aux mêmes lois que celles des joints.

4.5.1 - Rivets - Cas général (figure 8).
L'étanchéité n'étant pas réparable, elle sera doublée.

. Interposition sous tête
. Produit sur extrémité
. Empilage étanche.

- Rivets S.L (Huck Bolt). - Etanchéité doublée.
. Produit sous tête.
. Produit sur bague (et non dans l'alésage de la bague).
. Empilage étanché.

- Vis.

- Vis démontable. Etanchement réparable, étanchéité simple.
  - Vis de porte structurale.
  - Vis F.E. (fraisée étanche à gorge sous tête).

- Vis traversant un joint non apparent.

. Joint d'interposition.

On considère la vis comme traversant une pièce massive, par suite l'étanchéité se fera sous tête et la sécurité obtenue par enrobage de l'écrou.

. Joint injecté.

La pose du joint injecté se fera obligatoirement postérieurement au montage définitif de la vis. Si la vis n'est pas du type étanche, la tête sera recouverte de 2 couches.

- Ecrou.

. Normal.

L'écrou normal s'étanche après pose définitive à l'aide :
. de 2 couches de PR ou bien de 3 couches de PR si l'empilage et la vis ne sont pas eux-mêmes étanches.

. Prisonniers étanches.

Ce type n'existe pas en bande. Le capuchon qui le contient est toujours recouvert de 2 couches de PR englobant la tête des petits rivets de fixation.

4.6 - Portes des réservoirs structuraux.

. Portes à démontages fréquents (figure 10).

Ces portes sont étanchées mécaniquement par serrage d'un joint torique dans l'empilage. Les écrous situés à l'intérieur du caisson sont étanches à chapeaux rivés recouverts de 2 couches de PR.

Les vis sont normales, et se trouvent à l'extérieur du caisson.

. Portes à démontage rarissime (figure 11).

Ces portes sont montées aussi par serrage d'un joint torique et par des écrous non étanches.

Par contre, on réalise une sécurité à l'aide d'un cordon apparent situé soit dans l'interstice entre la porte et le repos de porte, soit en bordure de porte, cordon en forme de congé.

. Portes sans joint torique.

Elles sont montées avec des écrous non étanches, vis étanches et avec un joint injecté le long de la ligne de vis.

Dans tous les cas, le démontage implique la destruction des cordons de PR. Par suite le remontage impose d'attendre la polymérisation du produit frais avant les essais ou la mise sous carburant.

5 - LE PROBLEME DES FUITES.

. Etude de fuite.

Sur nos avions de combat, MIRAGE F1, MIRAGE 2000 par exemple, nous rencontrons des cas de fuites carburant que l'on répertorie afin d'en localiser les plus importantes et les plus fréquentes et d'en rechercher les causes et les solutions de réparation.

Les cas de fuite sont les suivants :

. Au niveau des vis étanches sur panneau de revêtement de voilure
. Au niveau du panneau non démontable de fuselage
. A l'angle de panneau de revêtement fuselage
. Au niveau de noeud entre nervure, longeron on longeronnet de voilure.

De nombreuses actions sont menées pour améliorer l'étanchéité de nos avions, notamment :

. La définition technique et les instructions de fabrication.
. Les principes d'étanchéité développés par la maintenance.
. La qualification du personnel.
. Les consignes de réparation.
. Les vérifications et essais.
. Le suivi des incidents.

Ceci permet de supprimer pratiquement toutes les fuites répétitives rencontrées en utilisation sur les avions, quelquefois aux prix d'une modification locale de conception.

L'expérience montre qu'une fuite bien réparée ne réapparaît pas. Les difficultés d'accès et la précipitation peuvent nuire à la qualité de la réparation.

. Types de fuites.

- Taches, formation due au carburant qui se charge d'impuretés.
- Suintements, grosses taches qui après essuyage au chiffon, réapparaissent avant une heure.
- Fuite "goutte à goutte" : fuites caractérisées par plusieurs gouttes dans l'heure.
- Fuites par ruissellements : écoulement abondant généralement localisé.

5.1 - REPARATIONS D'ETANCHEITE.

5.1.1 - Généralités.

Les fuites apparaissent en général dans les zones les plus chargées mécaniquement. Certaines jonctions sont très complexes (figure 12).

Les réparations doivent être confiées à un personnel familiarisé avec les principes d'étanchéité et les méthodes applicables.

Le succès de la réparation dépend des facteurs suivants :

. de la détection et de la localisation de la fuite
. de l'étude et de la méthode à appliquer
. de la réfection et de l'application minutieuse des joints d'étanchéité
. du mode d'utilisation des produits d'étanchéité.

5.1.2 - Recherche de fuites.

Généralement, la fuite de carburant est décelée au cours de l'utilisation de l'avion. Dans ce cas, il suffira de bien localiser et repérer l'endroit fuyard. Deux méthodes peuvent être utilisées pour détecter des fuites :

Première méthode.

. Pressurisation des réservoirs carburant à la pression nominale.
. Recherche au niveau des joints d'étanchéité des coupures d'éléments, des orifices d'injection et des éléments d'assemblage, des fuites à l'aide de la solution détectrice de fuites.
. Depressurisation.

Deuxième méthode.

. Effectuer le plein du ou des réservoirs puis pressuriser.
. Talquer la zone réputée fuyarde. L'apparition d'une auréole dans la zone talquée localise l'endroit de la fuite.
. Dépressuriser et vidanger le réservoir.

5.1.3 - Réparations.

A - Sur éléments d'assemblage.

(1) Vis. - Etanchée sous écrou et sous tête.
- Ne jamais resserrer une vis fuyarde.

(2) Rivets. Deux possibilités :

. Dépose de l'élément incriminé et remplacement par un élément étanche ou bien réfection de l'étanchéité au niveau de l'enrobage de la fixation.

B - Sur élément d'ossature.

(1) Cordon d'angle et cordon inter-tôle.

On enlève complètement la partie du cordon détériorée en le terminant par un biseau afin que son raccordement avec le produit d'étanchéité s'effectue correctement. D'une façon générale, le produit frais adhère bien sur les surfaces parfaitement dégraissées (tôles, peintures ou produits de scellement polymérisés).

(2) Cordon injecté.

L'injection ou la réinjection de PR se fait à l'aide d'un pistolet extrudeur à pression réglable sur lequel il est possible d'adapter différents embouts suivant l'accessibilité et le cordon à réaliser.

. Réalisation d'un cordon.

Il s'agit d'injecter avec la pompe d'injection à pression règlable, du PR par les trous existants jusqu'à ce que le PR sorte par le ou les trous contingus. Cette opération s'effectuera de trou en trou puis par un lissage afin d'éliminer l'excédent de PR.

. Réparation d'un cordon.

L'opération consiste à emprisonner le point de fuite entre deux trous d'injection existants en réinjectant du PR par ces trous.

5.1.4 - Problème de la corrosion microbienne.

L'apparition du phénomène est liée à la présence simultanée d'eau, dissoute ou non dissoute et de micro-organismes ou agents microbiologiques (ferro bactéries, bactéries sulfato réductrices, thiobacilles) qui se nourrissent d'impuretés minérales et organiques présentes dans ce milieu (produit d'étanchéité, résidus en suspension dans le kérosène...). Les produits biologiques engendrés par les bactéries attaquent les alliages d'aluminium et peuvent percer des tôles par affouillement local.

Ce phénomène est signalé principalement dans les réservoirs structuraux d'aéronefs stationnant dans les régions chaudes et humides. L'action conjointe des résidus biologiques des micro-organismes et de l'eau détruit le film protecteur appliqué sur les parois des réservoirs pouvant entraîner : des corrosions importantes, des modifications de la qualité du carburéacteur lui-même et provoquer le colmatage des filtres.

Quoi qu'il soit admis que le traitement carburant par une additivation anti-glace puisse jouer un rôle protecteur, il est parfois nécessaire de recourir à un traitement bactéricide à base de Bore pour prévenir et corriger les effets de ce type de corrosion surtout pour les avions effectuant des missions dans les pays tropicaux.

Cette corrosion ne peut être décelée que par des inspections très poussées des réservoirs à carburant qui sont entreprises en cas de colmatage de filtre ou suite à des analyses mettant en cause la pollution bactérienne.

Une bonne solution consiste à l'application d'une peinture barrière d'attaque bactérienne, ou mieux dans les zones de point bas à la mise en place d'une couche épaisse 1 mm de produit d'étanchéité.

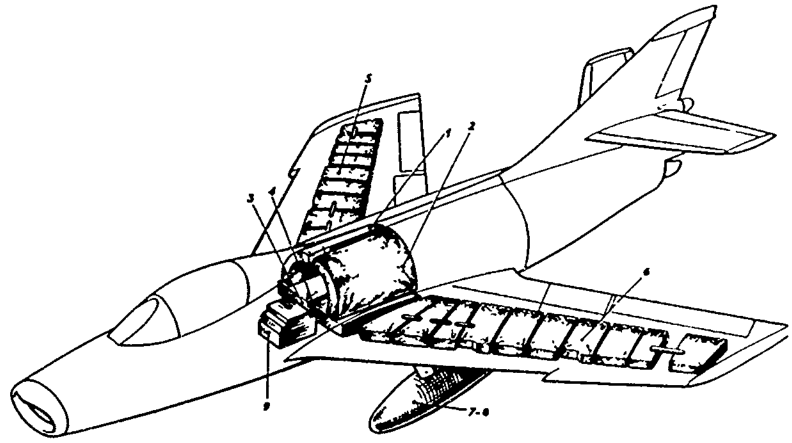
6 - CONCLUSION.

Les réservoirs structuraux présentent la solution moderne pour le stockage du carburant à bord. Les avantages ont été confirmés par une très longue expérience en vol. Rappelons :

- La simplicité de conception permettant la récupération des volumes tourmentés et même inaccessibles.
- La simplicité des intercommunications des transferts et des pressurisations.
- La longévité remarquable des produits de scellement.
- Les possibilités de réparations pratiques confirmées pour toutes les zones bien conçues et bien réalisées.
- Accessoirement, la mise en évidence de zones structurales a fort déplacement élastique révélée par des fuites.

Pour les structures avions, les améliorations viendront essentiellement des performances accrues des produits de scellement en fonction des besoins en température, résistances mécaniques, tenues aux nouveaux ingrédients et aux vieillissements.

SMB2 INSTALLATION COMBUSTIBLE



1 - 2 - RESERVOIRS de FUSELAGE (Nb 3)
3 - 4 - RESERVOIRS de PLAN CENTRAL (Nb 1)
9 - RESERVOIR de SOUTE (tolerie)
5 - RESERVOIRS dans 1/2 VOILURE DROITE (Nb 10)
6 - RESERVOIRS dans 1/2 VOILURE GAUCHE (Nb 10)
7 - 8 - RESERVOIRS PENDULAIRES (Nb 2)

FIGURE 1

SMB2 RESERVOIR SOUPLE

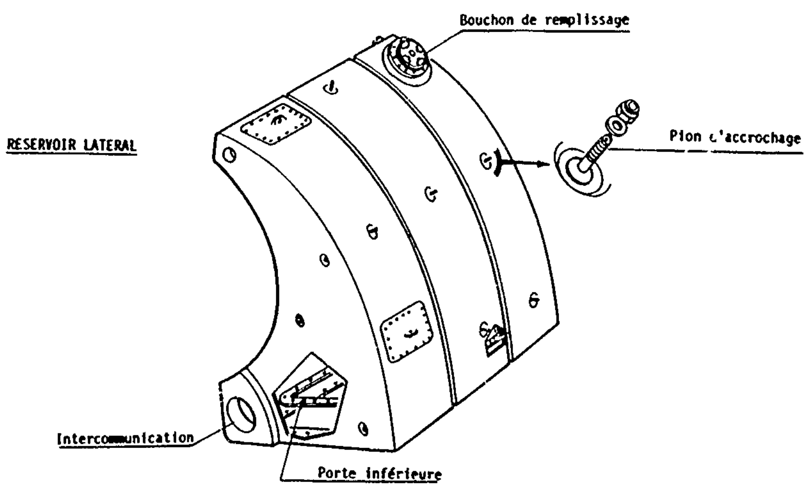


FIGURE 2

RESERVOIR SOUPLE

MIRAGE III

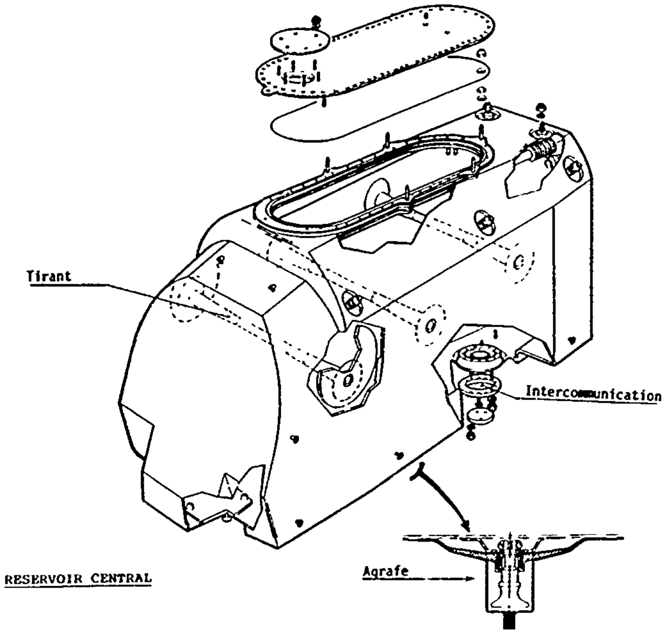


FIGURE 3

ENSEMBLE DES RESERVOIRS

LEGENDE

RESERVOIRS INTERNES Fuselage

Réservoir soute avant supérieur (1)
Accu de vol à "g" négatif (2)
Réservoir groupe fuselage G (3 4-5)
Réservoir groupe fuselage D (6-7 8)
Réservoir soute arrière en deux compartiments (9)

RESERVOIRS INTERNES Voilure

Réservoir plan central G (10)
Reservoir bord d'attaque G (11)
Réservoir plan central D (12)
Réservoir bord d'attaque D (13)

RESERVOIRS EXTERNES

Réservoir sous voilure G (14)
Réservoir sous voilure D (15)
Réservoir sous fuselage (16)

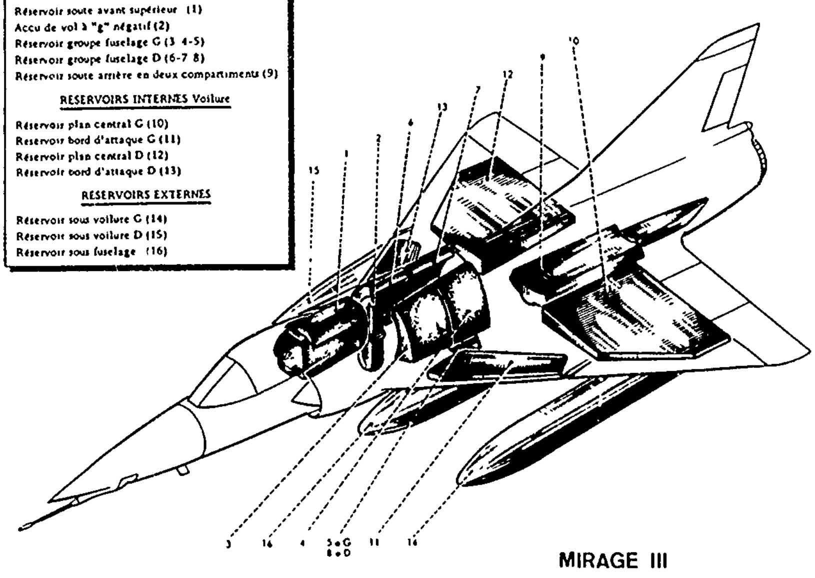
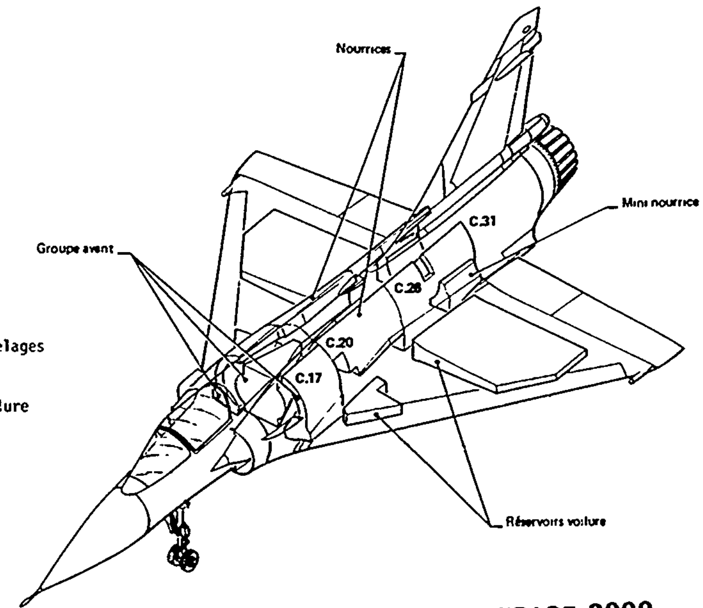


FIGURE 4

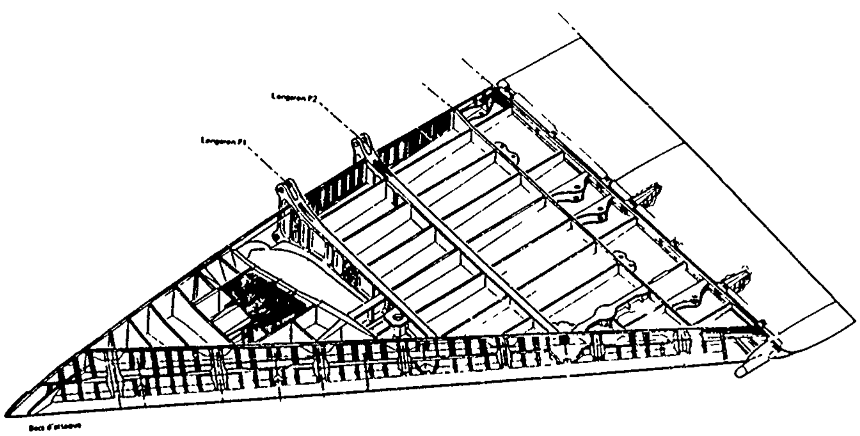
ENSEMBLE DES RESERVOIRS

7 réservoirs de fuselages
2 mini nourrices
4 réservoirs de voi!ure



MIRAGE 2000

STRUCTURE RESERVOIR VOILURE



MIRAGE 2000

FIGURE 5

JOINTS

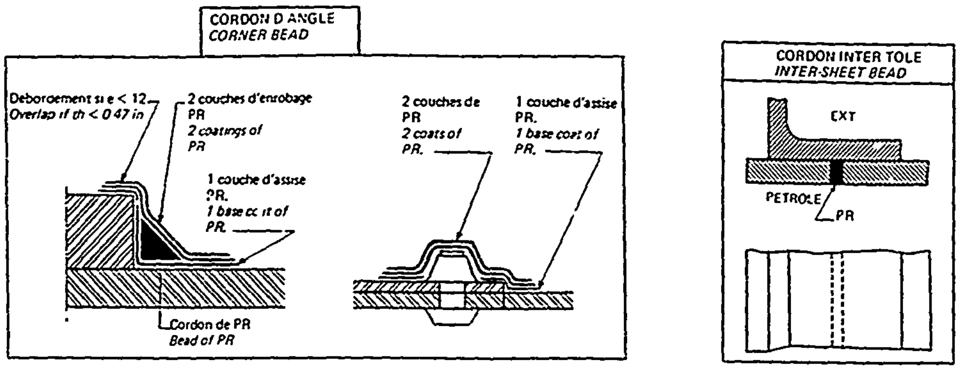


FIGURE 6

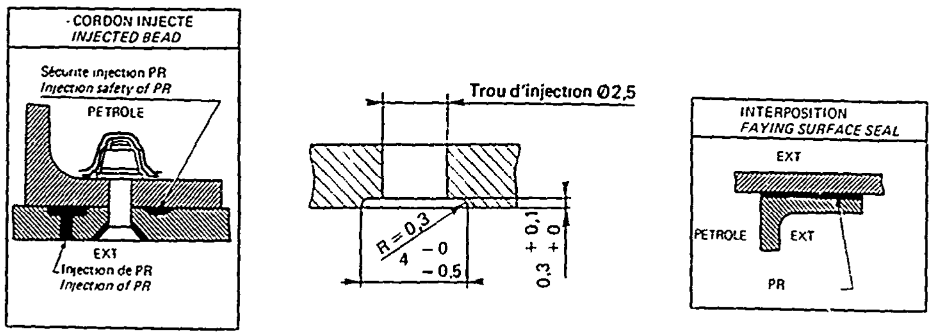
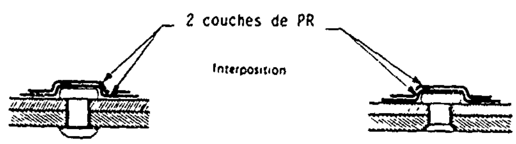


FIGURE 7

RIVETS STANDARDS



RIVETS MECANIQUES SUR EMPILAGE ETANCHE

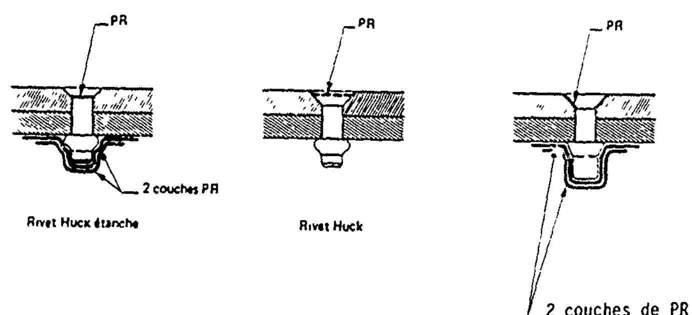
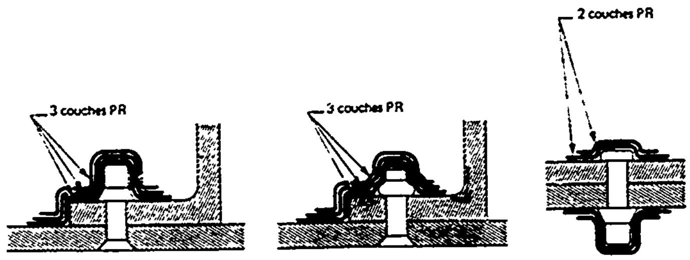


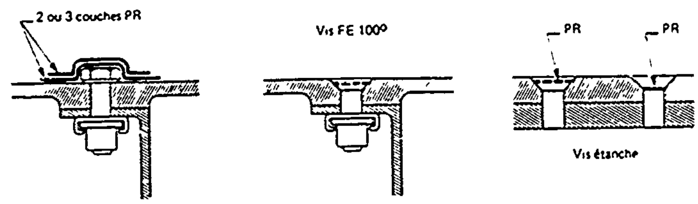
FIGURE 8

RIVETS MECANIQUES SUR EMPILAGE NON ETANCHE



VIS

Vis démontables



ECROUS

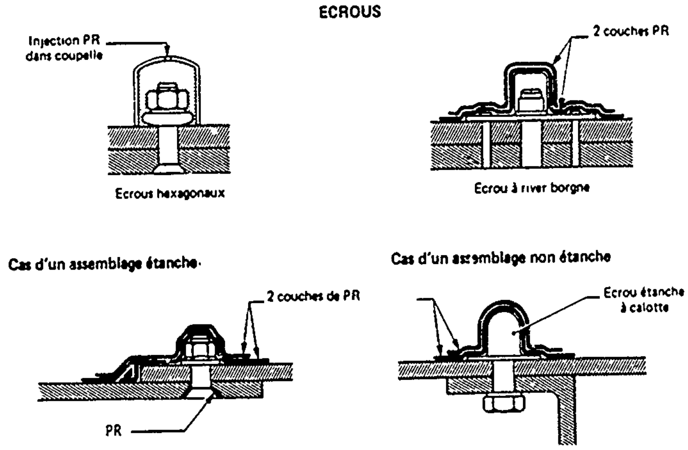


FIGURE 9

PORTE A DEMONTAGE FREQUENT

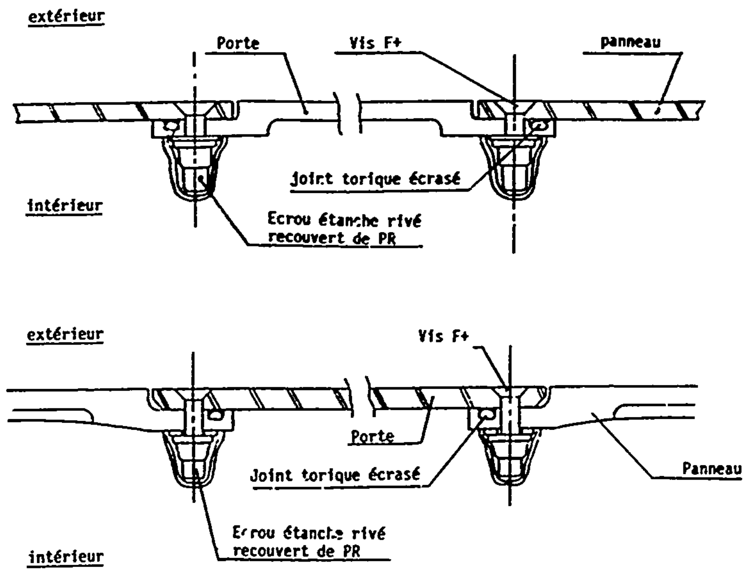


FIGURE 10

PORTE A DEMONTAGE RARISSIME

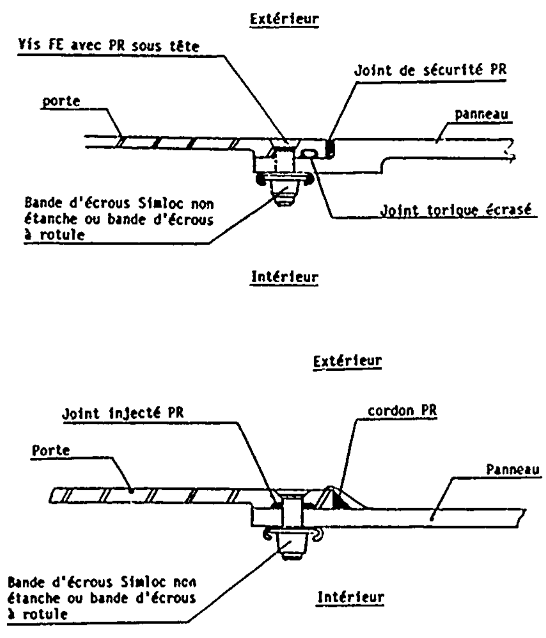
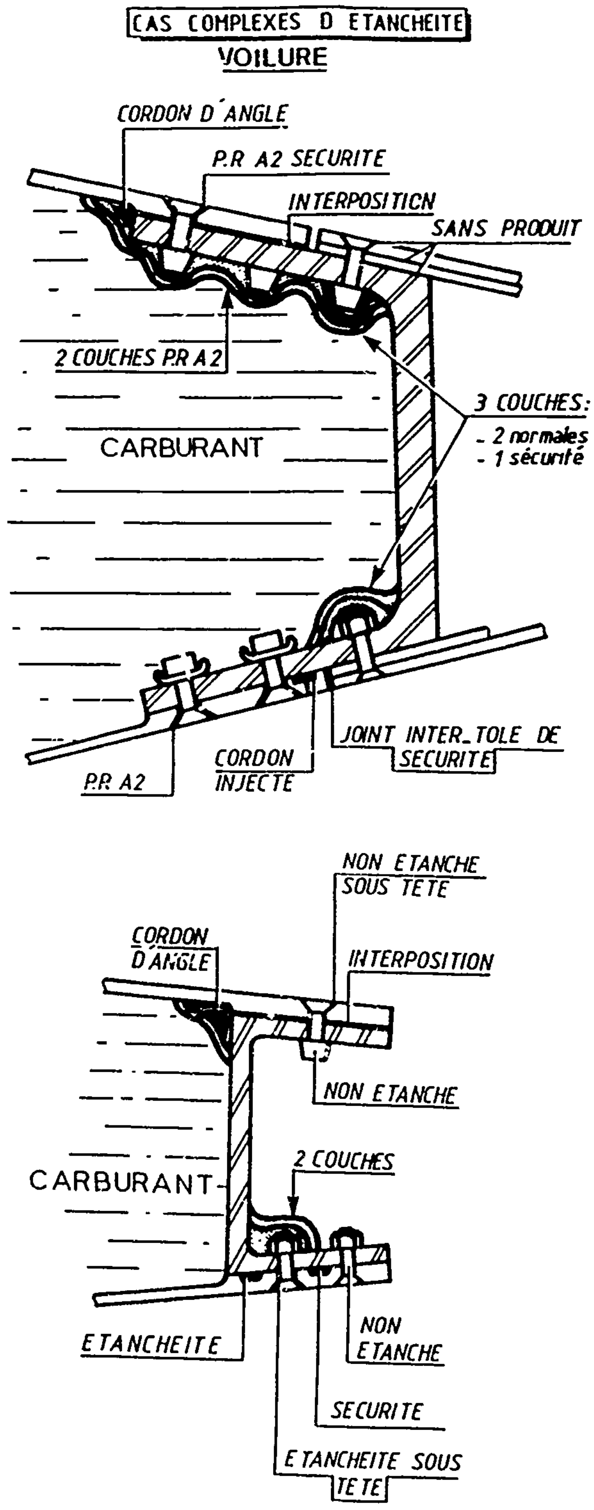


FIGURE 11



CAS COMPLEXES D ETANCHEITE
VOILURE
CORDON D'ANGLE
P.R A2 SECURITE
INTERPOSITICN
SANS PRODUIT
2 COUCHES P.R A2
3 COUCHES:
- 2 normales
- 1 sécurité
CARBURANT
JOINT INTER_TOLE DE SECURITE
CORDON INJECTE
P.R A2
NON ETANCHE SOUS TETE
CORDON D'ANGLE
INTERPOSITION
NON ETANCHE
2 COUCHES
CARBURANT
ETANCHEITE
NON ETANCHE
SECURITE
ETANCHEITE SOUS TETE

FIGURE 12

AIRCRAFT FUEL TANK CONSTRUCTION AND TESTING EXPERIENCE

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ABSTRACT

The evolution of aircraft structures manufacturing technology has moved the choice of solutions for fuel tanks, from welded sheet metal components to flexible rubber fuel cells up to nowaday when airplanes manufacturers are going to address their choices, toward more extensive adoption of integral fuel tanks.
This paper presents the AERITALIA experience in fuel tanks construction with a short view on flexible fuel tank applications (advantages and disadvantages) and the technological solutions adopted for integral fuel tanks construction and performances quality assurance.
The Integral Fuel Tanks are designed as primary structures to sustain high loads, therefore the critical target is to obtain a leak proof structure and to guarantee no leakage for the aircraft service-life.

1. INTRODUCTION

The evolution of aircraft structures manufacturing technology has moved the choice of solutions for fuel tanks, from welded sheet metal components to flexible rubber fuel cells, up to nowadays when airplanes manufacturers are going to address their choices toward more extensive adoption of integral fuel tanks.

- The modern fighter aircraft highly loaded structures are designed and built with the use of machined parts mainly, and with large utilization of composite materials; this design concept leads to obtain structural configurations that well perform fuel tank function if they are adequately sealed.

- The critical target is to obtain leak proof structures and to guarantee no leakage for the aircraft service-life.

- In the frame of the above mentioned evolution, AERITALIA experienced all the types of airplane fuel tank systems, since the welded sheet metal ones, typical of hystorical aviation machines and used up to second world war fighter aircraft and up to now for light general aviation machines.

- AERITALIA went to flexible fuel cells utilization in the following programs:

  F 86 K - SABRE DOG
  G 91
  F 104 G/S/TF - STARFIGHTER

- Integral fuel tank design and manufacturing began with the AERITALIA program G 91 Y during the sixties and have been consolidated through the application on the modern combat aircraft that have a mixed type of flexible fuel tanks in the fuselage and integral fuel tanks in the wing. (See FIG. 1).

- The next step of evolution will be the integral fuel tank system expanded to the whole airplane; in this direction the European aircraft manufacturers are going to develop the new generation air superiority fighter.

2. FLEXIBLE FUEL CELLS

The flexible fuel cells in the type of bladders without self sealing

capability have been largely utilized since early fifties and are currently adopted in the fighter aircraft fuel systems, particularly in the fuselages.
The evolution of the materials offers now flexible fuel cells with self sealing and crash resistance capability. (See FIG. 2, 3, 4).

2.1 Flexible fuel cells advantages

- Possibility of installation almost in each bay within the conventional structures, by means of predisposition of suitable access doors and after that the hollow walls have been properly prepared. (See FIG. 5).
- Possibility of remove the flexible fuel cells from the structure hollows turning them inside out in order to provide easy repair actions or quick replacement.
- Self sealing capabilities offer interesting operational advantages to the airplane in case of small damages produced by battle shoots.
- Crash and vibration resistance capability are also typical performances of the last generation of flexible fuel tanks.

2.2 Flexible fuel cells disadvantages

- High cost of the fuel cells.
- Difficulties of storing of the flexible cells either for the new parts than for the repaired ones.
- Critical aspect of the incoming inspection operations, this due to the high risk of fuel cells damaging as a consequence of the unfolding and refolding operations.
- Difficulties to perform acceptance inspection tests on the loose cell.
- Additional high costs for hollow walls preparation to provide fuel cells protection against damages caused by sharp edges and corners sometimes present in the structures. (See FIG. 6, 7, 8).
- Additional installation costs and risk of damaging due to fuel cells anchoring performed manually by very complex tying operations. (See. FIG. 9).
- Risk of damaging of the thicker reinforced zones of the flexible fuel cells where normally are attached the metallic fuel pipes and anchoring points.
- Possible porosities in the flexible fuel cell which are not easily detectable can produce in service leaks that are not so evident to be immediately discovered, but they can produce fuel diffusion in the metallic structures and fuel contamination or corrosion.
- Generally it is clear that the fuel tank system which adopt flexible fuel tank units is not a weight saving choice, because an additional component has to be put in the basic airplane structure.
  In term of airplane operational balance this means also more cost due to the inverse relationship between aircraft empty weight and payload.

3. INTEGRAL FUEL TANKS

- The beginning of the integral fuel tanks adoption took place when the aircraft structures had to become more stiff-efficient for to allow higher flight performances.
- The conventional structures assembled with a large number of sheet metal parts have been replaced by structures with a reduced number of components

assembled together that mostly are machined parts.

- Practically such a kind of structural solutions already are providing fuel tank functions, without the need to introduce any additional containing element like flexible cells.

- The big effort that has been done for the improvement of the integral fuel tanks performances has been addressed to find adequate assembling solutions, in order to built leake free structures and to guarantee no leakage for the aircraft service life.

- The new fighter aircraft which are going to be designed and developped for the years two thousands will have a larger application of integral fuel tanks, in the airplane zones where flexible fuel cells are at the present still used (i.e. fuselage).
  This is due to the advanced structural concepts based on intensive use of advanced composite materials will allow to obtain highly integrated structural components, with significant reduction of matched parts and fasteners application.
  These kind of structures are expected to be more seal-effective than the integral tanks built at the present.

4. AERITALIA EXPERIENCE

The first AERITALIA integral fuel tank design and manufacturing experience has been that of the G 91 Y - in the sixties.

- The central section of the wing structural torsion box has been designed for fuel tank capabilities, changing the previous project of the G 91 R, which was typical sheet metal structure, into the new concept of integral machined parts (wing panels).

- The G 91 Y integral fuel tank structure were made up by three subcomponents, (Left wing box/Central wing box/Right wing box) assembled together with high strenght fasteners in the interfacing ribs. (FIG. 10).
  Each box section was made up by integral machined light alloy panels, (upper and lower), front and rear spars and interfacing/closure ribs (Central box in FIG. 11).

- The fuel tank seal was assured by means of the following sealing methods.

  a) - All the surfaces protected by ALODINE 1200 and painted with corrosion preventive from fuel contaminants product PR 1560 per MIL-C-27725.

  b) - All the interfacing surfaces assembled with PR 1431 Type I sealant.

  c) - After assembling of the parts apply fillers of PR 1422 B2 per MIL-S-8802 sealant.

  d) - Head of fasteners protected with brush application of PR 1422 A2 per MIL-S-8802 sealant.

  e) - Cleaning and degreasing of the internal surfaces and application of PR 1005 L (BUNA N) sealant with washing method.

- The fuel tank testing was performed with air pressurization at 31 MPa maintained for a time of 15 minutes.
  Final test was performed looking for leaks with the wing filled up with JP4 fuel.

4.2 AERITALIA Integral fuel tank technology in the EIGHTIES YEARS

AERITALIA experience with G 91 Y on integral fuel tank has evoluted in the design and construction of modern MULTI ROLE COMBACT AIRCRAFT WING.

4.2.1. Integral Wing Tank Design

The wing tank is an integral part of the wing torsion box structure.
The torsion box consists of aluminium alloy structure bolted to the high strength titanium lugs in the wing/fuselage attachment zone.
The fuel compartment in the torsion box is formed by the front and rear spar, the first rib at the wing root and the last rib at the wing tip, and the lower and upper skin panels.
The outer compartment adjacent to the wing tank at the wing tip, is used as a vent box.
The upper skin panel has access doors for maintenance operations. (See FIG. 12).

4.2.2 Integral Wing Tank surface protective treatments and sealing methods adopted

To all surfaces is applied an anodising treatment.
All tank surfaces not in contact with fuel have a coating of epoxy primer followed by an epoxy top coat application.
To the surfaces in contact with fuel, including sealed interfaying surfaces, is applied a sprayed-one coating of polyurethane protective coating resistant to microbial corrosion, PR 1560 MC per MIL-C-27725.
Holes for removable fasteners in contact with fuel are protected by a yellow chromate conversion coating.
Permanent fasteners like HI-LOK are installed with a polysulfide sealant PR 1431.
The interfaying parts are assembled with PR 1431 Type 1.
One or more coats of PR 1422 A per MIL-S-8802 sealant are applied on fuel side fasteners heads, nuts or anchor nuts. (See FIG. 13, 14, 15).
Joint lines are coated by PR 1422 A-2 sealant, followed by a fillet of PR 1422 B and over the fillet two more coatings of PR 1422 A. (See FIG. 16 "scheme of sealing methods adopted in the wing integral fuel tanks").

4.2.3 Quality problems at the beginning of production

- At the beginning of the production, many problems due to: low skill of the operative people poor experience on the utilization of the products, lack of facilities and suitable equipment for the right polymerization of the products utilized were causes of many fuel leaks.

Solutions adopted

- For the operative people, were done up to nowadays also team training for the mixing and application of the sealants utilized, explaining to them that the sealing is important as any other operations on the airplane construction.
- Better finish of the coupled parts with improvement of the allowance with more restricted tolerance values.
- Improvement of the sealing equipments - taking into consideration the environmental conditions for the right polymerization of the products utilized as far as temperature and humidity are concerned. (See FIG. 17, 18, 19, 20).
- Adoption of semkit products instead of standard sealant container with remarkable improvement of:

  a) - Safety dosage of sealant and catalyst;

  b) - Better quality and repeatability of the mixing operations.

- c) - This choice, even if more expensive, avoids the usage of expired products.

4.2.4 Testing methods on assembly line

The test carried out to detect Leakage are performed on two stations of the wing assembly line.

a) - The first inspection is performed at the end of the structural wing box assembly, after at least 72 hours from the sealants application.

b) - The second inspection is performed at the end of the equipment systems installation.

- Both the tests are performed pressurizing the wing box integral fuel tank with air and freon mixture at a pressure of 28 KPa.
- In this phase it is important to maintain the pressurization for at least 30 minutes.
- During the test all the joint lines are inspected with a leak detector and a soap water solution.
- If leakages are detected, the area must be carefully dried using a cloth, corners and recesses must be blownthrough with compressed air and must be dried.
- The leakage must be carefully observed since several individual leakages may occur in the same area.
- All types of leaks must be sealed, stains and seepages need not to be sealed immediately, but are to be thoroughly checked.
- Drips and running leaks are to be sealed immediately.
- If no leakages are detected the wing goes to subsequent station.

4.2.5 Testing method before wing delivery

- Before delivery to the Airplane Final Assembly Line the wing is inspected with another method called "Comparison method with a standard wing".
- This test is utilized for to evaluate the volume of eventual leakages comparing the production wing with a sample wing which has been already tested with fuel and without leakages. (See FIG. 21).
- The test is performed using: air and freon mixture at a pressure of 35 KPa and a leak detector, this scheme and the picture are shown in FIG. 22, 23).
- The validity of this test is based on the fact that it is possible to eliminate the negative influence of atmospheric pressure and room temperature.
  The consequences due to room temperature variation are deleted for the following reasons:

  a) - Equal structures

  b) - Equal thermic inertia

  c) - Equal fluid volume

  d) - Equal pressure variation on both wings at the change of the room temperature
- This comparison method not only gives accurate results as a leak test performed with the fuel, but it is more severe because the wing integral fuel tank is tested with pressurized gas mixture.

The test performed with a comparison method gives the following advantages:

a) - Rapidity on repair when it is required.

b) - Absence of explosive mixture on the wing tank.

c) - Safety handling.

d) - Long time storage (avoiding periodical explosivity check and periodical washings neutralization).

5. CONCLUSIONS

- These experiences are the background that AERITALIA put as basis for the design and manufacturing development of aircraft fuel tank in the frame of the new generation defence aircraft.

- In particular, as already told before, the aircraft structures of the future will have a lot of highly integrated carbon fibre components, a significant reduction of fasteners, higher stiffness, which together will provide higher seal performances.

- The new construction technologies and the adoption of new materials will give the above mentioned advantages if the assembling concepts and sealing products/methods will be a specific target of research and development.

- In this field AERITALIA is sharing research and development activities and is exchanging high volume of technical informations with the most important European Aircraft Manufacturers.

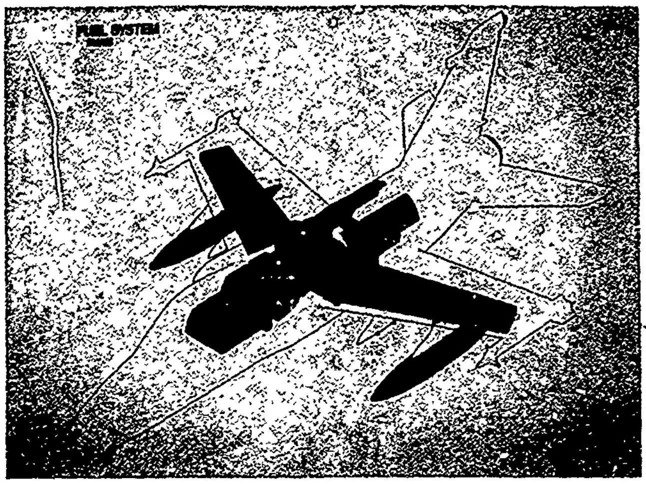


FIG.1- MODERN DEFENCE AIRCRAFT FUEL TANK SYSTEM

FIG.2- TYPICAL FUSELAGE FLEXIBLE FUEL TANK

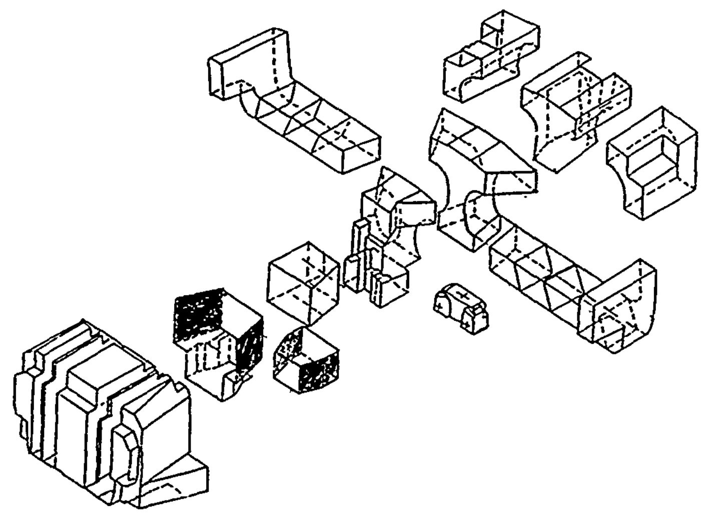


FIG.3

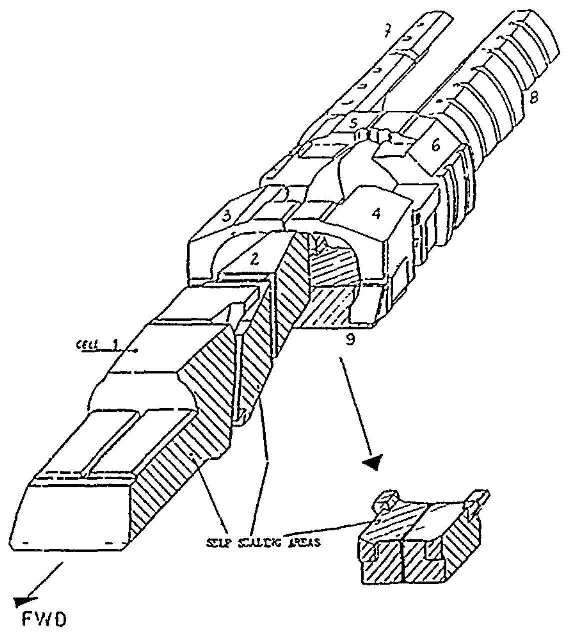


FIG.4

FIG.3&4- FLEXIBLE FUEL CELLS LOCATION IN TWO MODERN DEFENCE AIRCRAFT

FIG.5- FLEXIBLE FUEL CELL INSTALLED IN THE F104 STARFIGHTER FUSELAGE

FIG.6- HOLLOW WALL PREPARATION

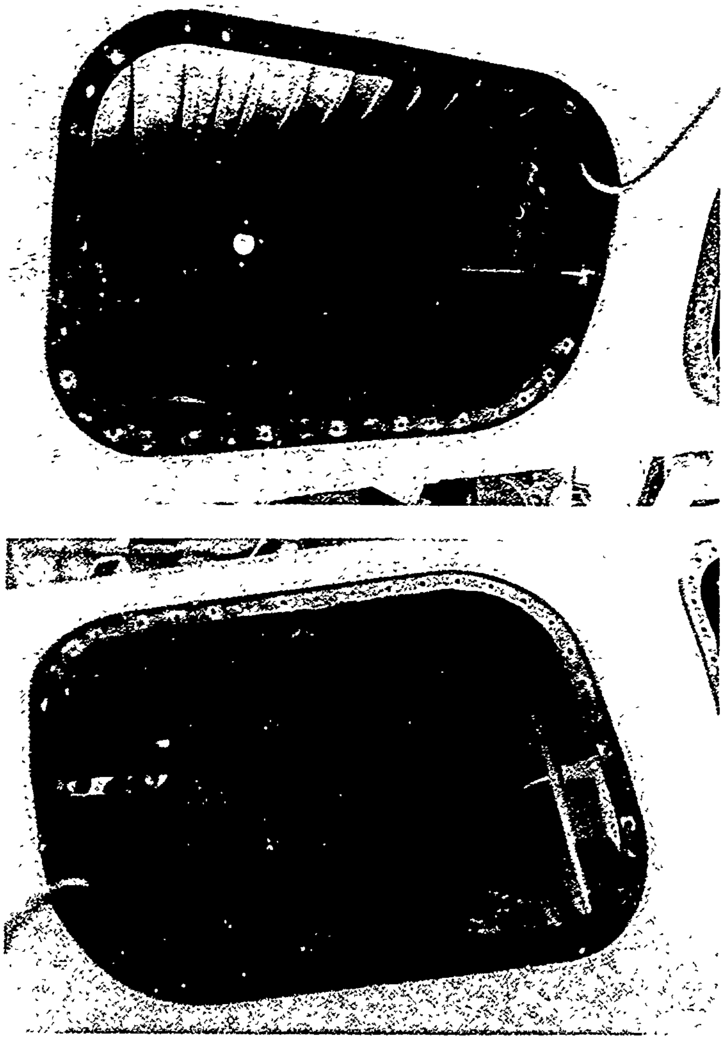


FIG.7 & 8- HOLLOW WALL PREPARATION

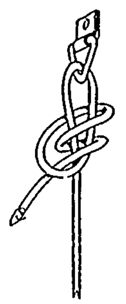


FIG. 2
STARTING KNOT

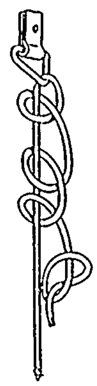


FIG. 3
FINAL KNOT

FIG.9- TYPICAL ANCHORING KNOTS

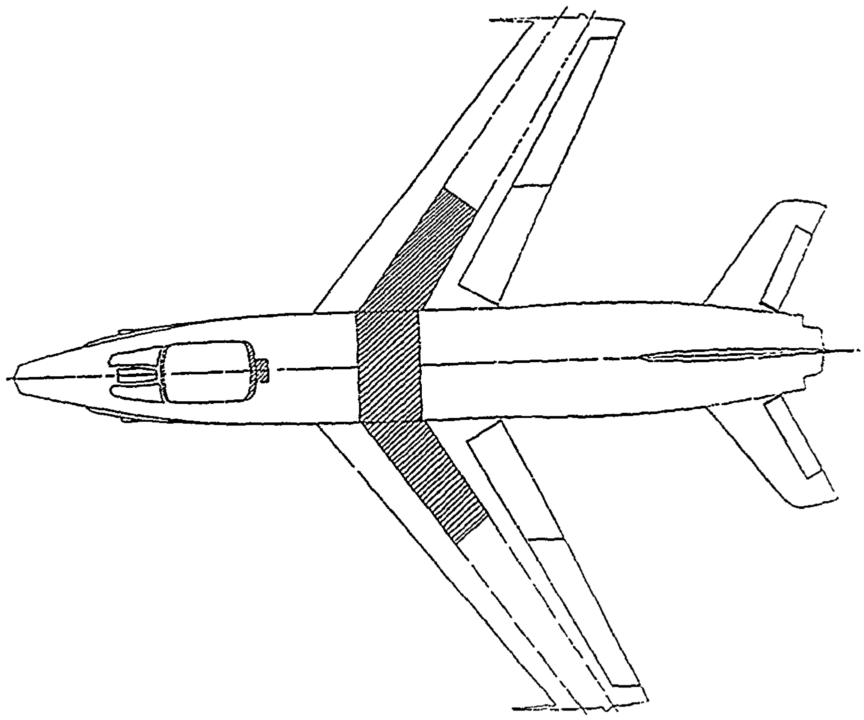


FIG.10- G91Y INTEGRAL FUEL TANK LOCATION

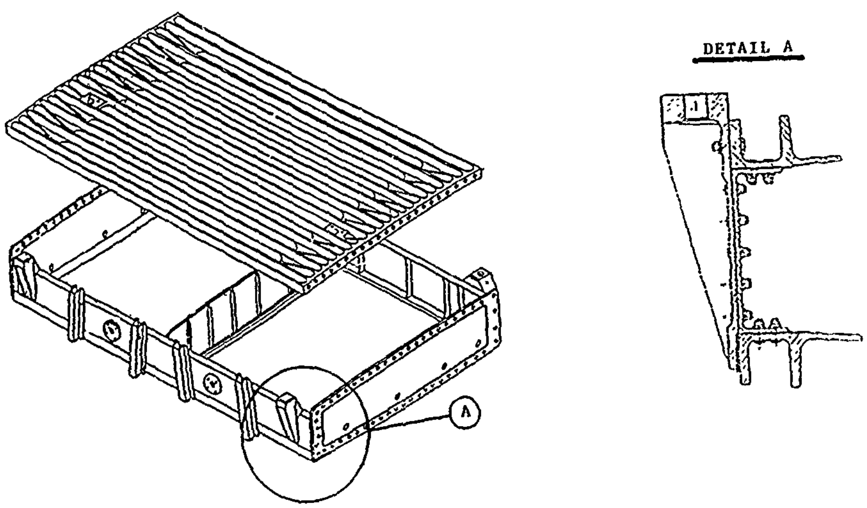


FIG.11- G91Y INTEGRAL FUEL TANK IN THE WING CENTRAL SECTION

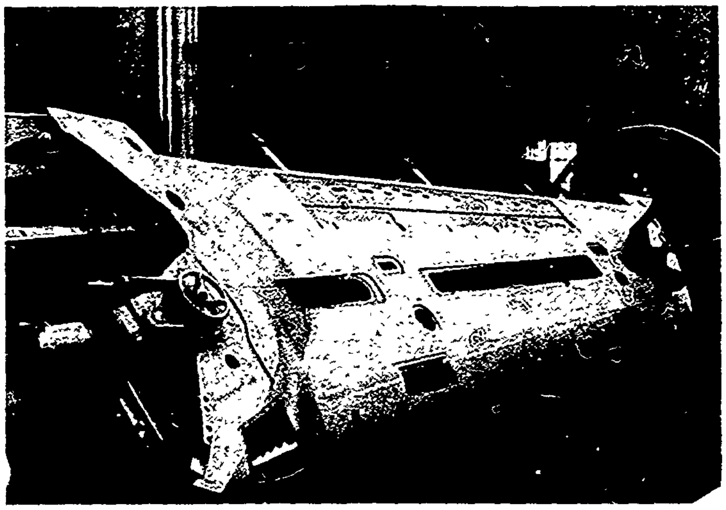


FIG.12- MULTI ROLE COMBAT AIRCRAFT WING INTEGRAL FUEL TANK

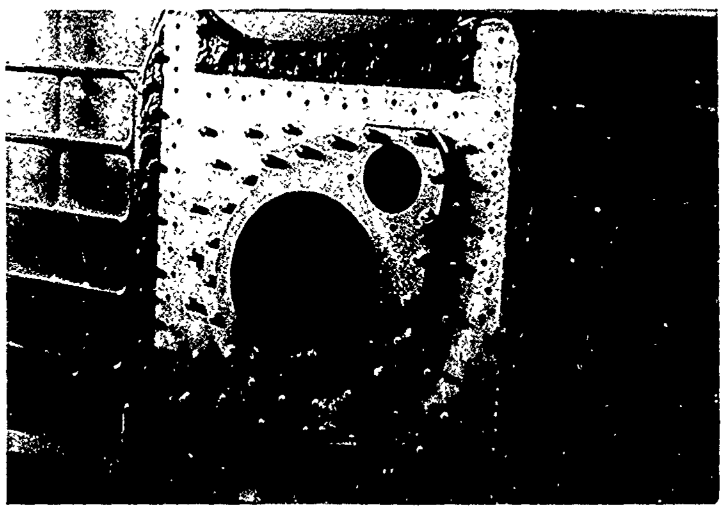


FIG.13- WING INTEGRAL FUEL TANK SEALING METHODS

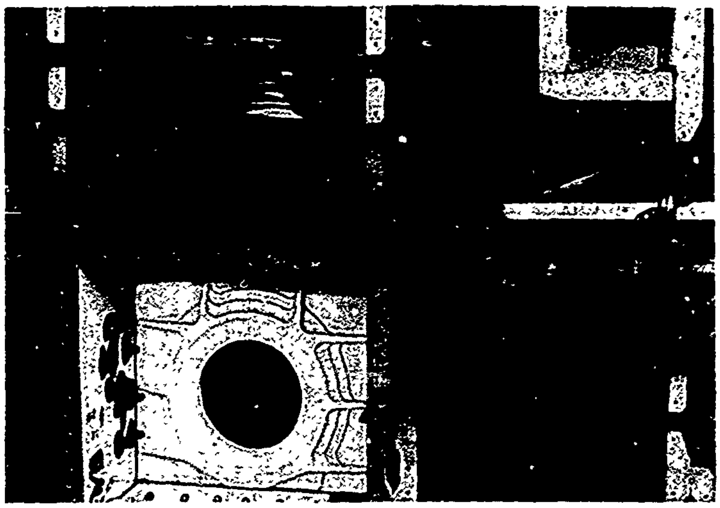
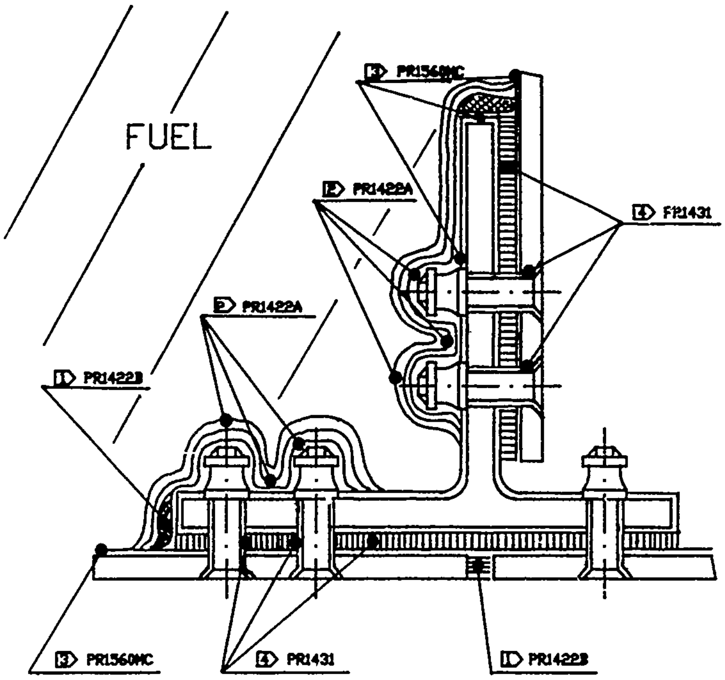


FIG.14- WING INTEGRAL FUEL TANK SEALING METHODS

FIG.15- WING INTEGRAL FUEL TANK SEALING METHODS



1 PR1422B SEALING COMPOUND ACCORDING TO MIL-S-8802.TEMPERATURE RESISTANT,INTEGRAL FUEL TANKS AND FUEL CELL CAVITIES,HIGH ADESION

2 PR1422A SEALANT MATERIAL ESPECIALLY DEVELOPED FOR USE OVER A TEMPERATURE OF -65 F +275 F WITH OUSTANDING RESISTANCE TO AIRCRAFT FUELS(GASOLINE AND JET-FUEL),LUBRICATING OILS AND DETERIORATION BY THE SATURATION OF DIPHOSPHATE ESTER TYPE HYDRAULIC FLUIDS.CLASS A IS FOR BRUSHING.CLASS B IS FOR FILLETING.

3 PR1560MC COATINGS CORROSION PREVENTIVE ACCORDING TO MIL-C-27725 TYPE 1 CLASS B FOR AIRCRAFT INTEGRAL FUEL TANKS.USED AS A PROTECTIVE COATING FOR AIRCRAFT INTEGRAL FUEL TANKS AGAINST CORROSION FROM FUEL CONTAMINANTS. FOR USE IN SERVICE TEMPERATURE RANGE OF -65 F TO +275 F.

4 PR1431 SEALANT FOR USE AS A FAYING SURFACE SEALING COMPOUND IN INTEGRAL FUEL TANKS AND PRESSURIZED CABINS,DEVELOPED FOR USE OVER A TEMPERATURE RANGE OF -65 F +275 F WITH EXCELLENT RESISTANCE TO AIRCRAFT FUELS (GASOLINE AND JET-FUEL),LUBRICATING OILS,AND HAS RESISTANCE TO DETERIORATION BY THE SATURATION OF DIPHOSPHATE ESTER TYPE HYDRAULIC FLUIDS (SKYDROL).

FIG.16- SCHEME OF SEALING METHODS ADOPTED IN THE WING INTEGRAL FUEL TANK

FIG.17- SEALING APPLICATION EQUIPMENT

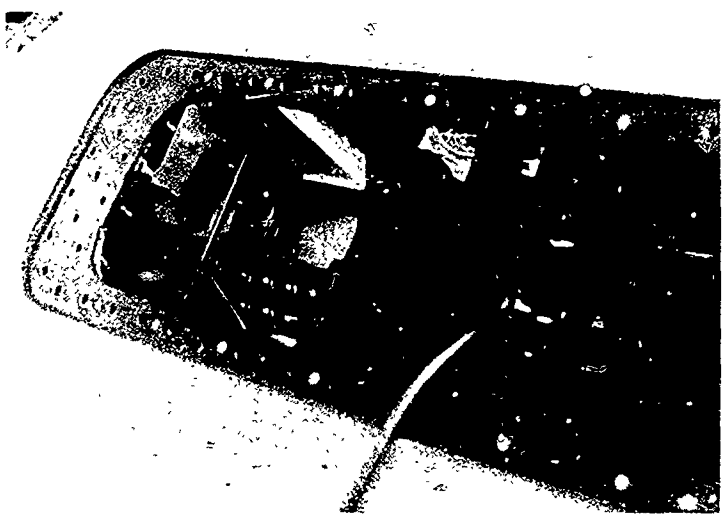


FIG.18- SEALING APPLICATION EQUIPMENT

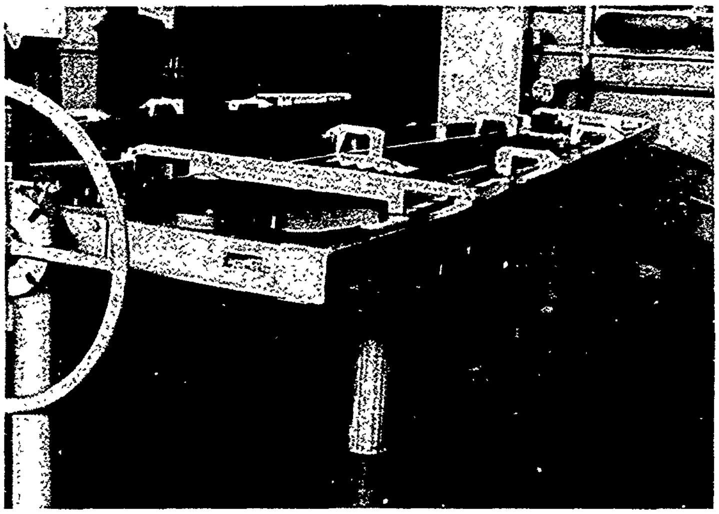


FIG.19- SEALING APPLICATION EQUIPMENT

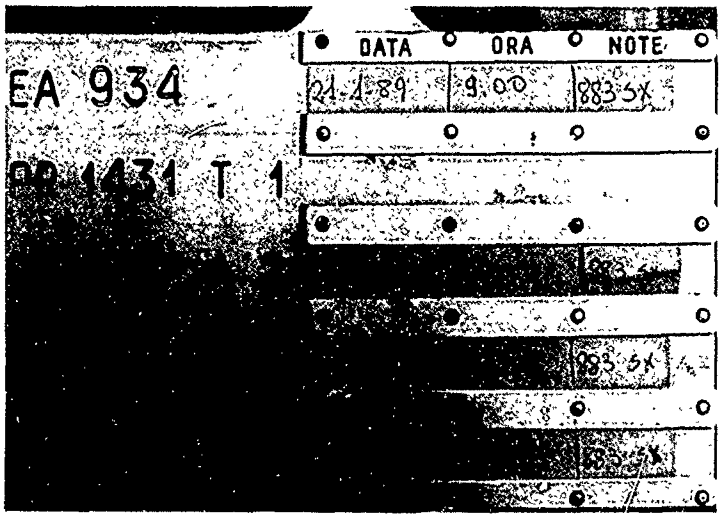


FIG.20- SEALING PROCESS CONTROL CARD

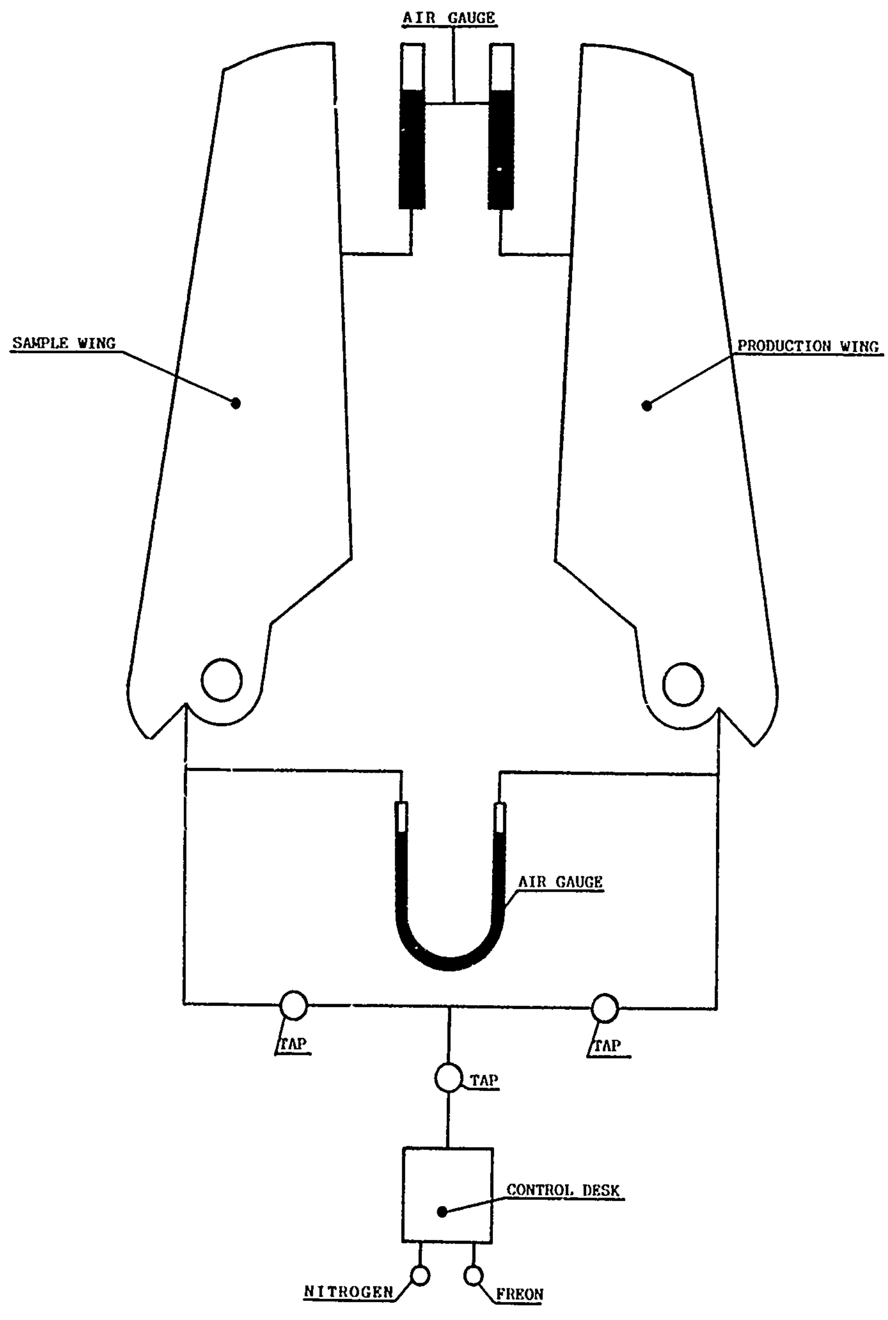


FIG.21- COMPARISON METHOD WITH A STANDARD WING

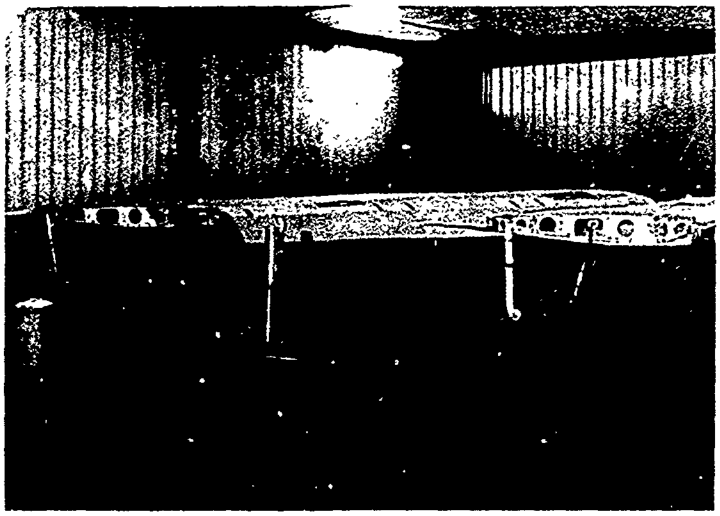


FIG.22

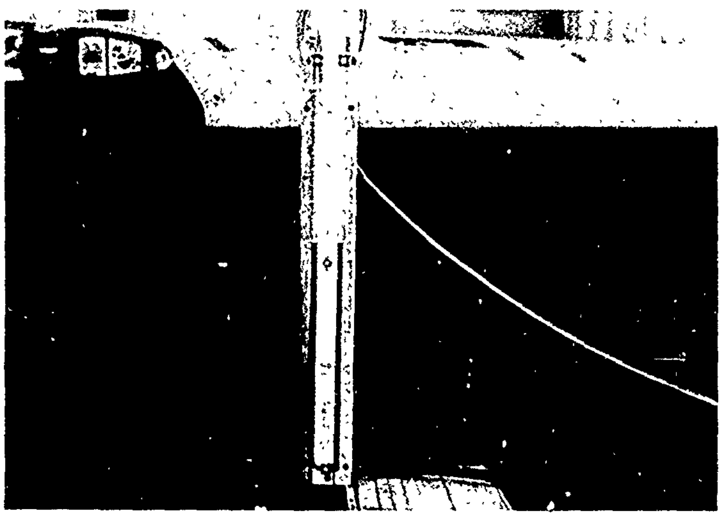


FIG.22 & 23- COMPARISON METHOD WITH A STANDARD WING

THE REPAIR OF AIRCRAFT INTEGRAL FUEL TANKS IN THE RAF
A USER'S VIEW OF FUEL TANK TECHNOLOGY

by

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INTRODUCTION

1. The sealing and repair of aircraft fuel tanks has been a thorn in the side of aircraft maintenance personnel for a considerable number of years. In the Royal Air Force in particular, repairing and resealing integral fuel tanks has always been difficult and has frequently required several attempts to achieve an acceptable seal. As a result the Royal Air Force currently spends in excess of £1.5 million each year in repairing and re-repairing leaking aircraft fuel tanks. In justifying this considerable expenditure, it would be easy to conclude that all our problems resulted from poor design, ineffective sealants, poor information or even bad weather! However, although all of these factors play a part in repair procedures, we also generate some problems for ourselves, and these require considerable commitment on the part of our managers to resolve. We have already made some progress in resolving the more critical of our problems, and our success rate in effective, long-term repairs has begun to improve. However, we expect the process of gradual improvement to continue for the foreseeable future.

2. In order to achieve this improvement, we have summarised a number of areas of concern, beginning with background to fuel tank repair in the RAF, and including Health and Safety problems, leak testing, tank venting, surface preparation and resealing. In each area we are continually improving both equipment and procedures in order to reduce aircraft downtime and improve repair effectiveness at all depths of maintenance. Finally, we have looked at the problems generated by aircraft design, and in particular access provided to integral fuel tanks. As in the other areas, we have identified problems and suggested improvements for future aircraft a well as highlighting the reliability and maintainability implications of poor design.

AIM

3. The aim of this paper is to document the problems faced by Royal Air Force maintenance engineers in repairing aircraft integral fuel tanks.

BACKGROUND

REPAIR POLICY

4. Integral fuel tank repair in-service is a surprisingly complex subject having several facets, each of which contributes its own particular area of difficulty in determining a clear repair policy. Indeed, the very definition of a repairable fuel leak is highly subjective; for example, what constitutes a fuel leak, and how bad does it have to be before any repair action is necessary? Who is going to repair a leak, to what depth and at what level in the maintenance organisation? Finally, but most importantly, how long will the repair take and how effective will it be in keeping the aircraft available for tasking in the long-term?

5. Whilst all of these questions are being addressed on a daily basis, local constraints of timescale and repair effectiveness are frequently injected into the local decision-making process, and often dictate the repair procedure. Even when a decision to carry out a repair has been made, rapidly changing operational factors such as aircraft availability and flying commitments frequently combine to reduce the time allotted to complete the repair. Unfortunately, as the main factors which determine the repair time; finding the leak and venting the tank, are fixed it is only possible for local managers to reduce aircraft downtime by reducing sealant curing times below their recommended levels; this usually results

in a temporary improvement in serviceability state at the expense of a permanent repair.

TECHNIQUES

6. In themselves, these factors affecting fuel tank repair present a considerable barrier to the quick and effective recovery of aircraft with leaking or damaged fuel tanks, both in peacetime and in a war scenario. However, in the past they have been compounded by the poor specialist knowledge often possessed by the tradesmen carrying out the repair. Basic knowledge, such as the correct sealant to use, surface preparation, sealant application, curing cycle and curing environment, was often sketchy or totally absent amongst our front-line tradesmen, with depot repair little better. In most repairs, correct or even adequate surface preparation is rarely achieved, whilst the use of adhesion promoters prior to the application of new sealant is not even mentioned in most of our repair manuals. Furthermore, the wrong sealant for a particular repair has frequently been specified, or the correct sealant has been applied in the wrong circumstances or environment. Finally, the correct methods of enhancing cure times by using controlled temperature and humidity in a hangar or hardened shelter are often not available at the front-line, or are not used effectively when tight timescales apply to a repair. In the past these problems have resulted in a largely self-generated unsatisfactory approach to the repair of integral fuel tanks. However, in order to move forward, we have addressed and improved each area in turn, although we have some way still to go if we are to achieve fully effective repairs coupled with acceptable aircraft downtimes and manhour costs.

TRAINING

7. In order to improve our knowledge of repair techniques, we have completed an in-depth study of matters such as surface preparation, the use of adhesion promoters and primer, curing environments and curing times, and have included their principles as part of our formal technician training courses. Data from our maintenance analysis establishment indicates that we currently spend in excess of 30,000 front-line manhours each year in repairing and re-repairing aircraft fuel leaks and improvement in the skill level of our tradesmen should reduce this figure and show a significant cost benefit, in addition to improving aircraft and manpower availability on our front-line flying units.

SEALANTS

8. In addition to studying procedures, we have also established the need for improved sealants for integral fuel tanks, both for new applications and for improved repair of existing problem tanks. In this context it is also essential to select the correct sealant to match the type of tank, the method of application and the local environment. Of the 4 basic types of sealant described below, the brushable and extrudable forms are traditionally the most widely used within the RAF:

a. Brushable sealant is applied with a short, stiff brush and worked into the surface with a small circular motion. The sealant should have a maximum thickness of 1/16th of an inch or less. Brushable sealants are used both as a base coat and a top coat for extrudable sealants; they may also be used in areas inaccessible to an extrusion gun, and around metal fasteners or seams.

b. Extrudable sealants are filleting sealants for sealing joints and seams, and are normally applied with an extrusion gun. They may also be applied with a trowel, and often are!

c. Faying surface sealants are used on overlapping joints and are therefore

mainly applied during manufacture or major repair. They are applied during jointing by extruding a continuous band of sealant across the surface before fastening the surfaces together. The surfaces must contain a continuous layer of sealant and not be sealed by the final fillet of sealant around the edge of the joint. As an alternative to these sealants, an expanded PTFE tape is under investigation for jointing both metal and composite structures.

d. As a relatively new technique sprayable sealants have not, until fairly recently, been used within the RAF for integral fuel tank sealing. Within the last year however, they have been used with some success on the Jaguar, Buccaneer, VC10 and soon we hope, the Harrier GR5. When spraying sealants, thickness must be built by multiple layers, not heavy spraying.

9. As an aircraft repairer rather than a manufacturer, we need improvements to all of our current range of sealants to enhance their adhesion to both composite and metal structures, improve flexibility to cope with flexing of tank structures under load, better application techniques, including spraying, and shorter curing times within wider environmental margins. In general, sealant manufacturers have responded favourably to our approaches, with the larger specialist companies already conducting research along the lines we were advocating and developing sealants with improved sealing properties coupled with shorter cure times and better environmental tolerance. However, the smaller manufacturers, or those not specialising in sealant manufacture, seem to be lagging well behind the specialists, with some marketing 'new' products which are similar to long established products and offer only minor advantages over those already in use.

REPAIR PROCEDURE

HEALTH AND SAFETY

10. In order to ensure that we make the most of new or improved fuel tank sealants, we have gathered information on the major repair procedures currently used in the RAF. However, before detailing these, we believe that it is essential to examine the safety aspects of repair. Health and Safety legislation is continually being revised to improve operator safety, to prevent practices which are injurious to the health of those in the repair area and to prevent wider environmental damage. As a result, Health and Safety measures involve a considerable commitment in terms of time, effort and equipment to implement. Nonetheless, we believe that such measures are a vital part of fuel tank repair and they should be implemented in full.

11. In implementing these measures, we recognise that the dangers of fire and explosion and the toxic effects of vapours during repair are very real, and every safeguard must be applied to prevent accidents. In view of the hazards presented by aircraft fuels, corrosion inhibitors such as strontium chromate and solvents such as Methyl-Ethyl Ketone (MEK), toluene and naptha, we insist that all fuel tanks are vented to a safe level before repair work commences. Even then our regulations require breathing apparatus to be worn by repair personnel, ventilation to be continued, vapour levels to be monitored, and a safety man positioned to maintain continuous visual or oral contact with personnel inside the tank. Finally, each repair unit has a tank rescue kit available, with pre-determined rescue procedures, should a tradesman be overcome by fumes whilst inside a large tank.

LEAK TESTING

12. The repair process proper begins with leak testing, which is generally a difficult and time-consuming business. Constant defuelling, refuelling and

venting, attaching and removing special blanks, covers and ground equipment, and the need to remove components for access all add considerably to both the manhour cost and the aircraft downtime. We currently use several methods of leak testing integral fuel tanks in the RAF and these vary considerably in difficulty and application time:

a. We use seep and pressurisation tests to pin-point a supected leak, to confirm the success of a repair or to confirm post-maintenance tank integrity. The fuel tank is refuelled and either pressurised with air (up to 0.3 bar) or left to stand. Suspect areas are wiped dry and a whiting solution, usually dye penetrant developer, chalk or talcum powder is applied; any leak will form a stain on the whiting solution.

b. Vacuum testing is the opposite process to the seep and pressure tests described above. A combination of vacuum and pressure testing is often necessary where a leak has 'tracked' behind sealant or the aircraft structure, giving separate internal and external leak points. In addition, we use a wet vacuum test on some of our problem aircraft such as the Harrier and Buccaneer, where the normal access panels can be replaced by special-to-type clear view panels and domes and plastic mirrors placed in the tank to aid vision. The tank is refuelled, a vacuum is applied and a check made through the clear view panels for air bubbles drawn in through the skin. Unfortunately, we find difficulty in getting sufficient light into the tank to see into remote areas and behind tank components.

c. A further development of vacuum testing involves the use of flourescent dyes to follow tracking leaks along fillets and through interfays. In this system the dry tank is sealed and evacuated, and flourescent dye brushed or sprayed onto external leak points. The vacuum is maintained for several hours, and the dye kept moist. When the tank is opened, an ultra-violet lamp indicates the internal leak points, and tracks can be easily followed as old sealant is removed.

d. The latest leak detection method introduced to the RAF is an enhancement of the wet vacuum test. This uses a Videoprobe 2000, which comprises a miniature solid state camera located at the end of a 13mm diameter flexible tube, a light source, an image processor, a visual display unit and a video recording system. Thb system allows the camera to be inserted through restricted openings or into confined areas to provide a high quality colour image on a remote VDU screen. Two-axis viewing head controls are provided at the operator's position which permit remote movement of the camera both to allow the operator to view in a desired direction and to aid the movement of the flexible tube and viewing head past obstruction. Some aircraft manufacturers currently use similar equipment to enable operators to see into remote and narrow areas such as the Eurofighter prototype centre fuselage fuel tank. In the RAF, the Aircraft Integrity Monitoring Squadron of the CSDE are co-ordinating further development of the videoprobe for a wide range of applications.

e. Arcton gas testing is mainly used on bag tanks, but is also used to test Nimrod aircraft integral tanks. The tank is pressurised with Arcton and the external seams checked with a halogen leak finder. As this process is both costly and environmentally damaging, it is not extensively used.

VENTING

13. Once the leak paths have been detected, but prior to carrying out any work in aircraft integral fuel tanks, the tanks concerned must be fully ventilated to remove residual fuel vapours to a designated safe level. In addition, ventilation

must continue whilst work is being done in the tank, and vapour levels must be checked regularly. The instructions for fuel tank venting in individual aircraft maintenance manuals vary from a simple statement to 'ventilate with clean, dry air until the tank is dry'. to a comprehensive procedure covering all aspects of fuel tank ventilation. Of the 2 traditional methods of venting fuel tanks, air suction is not very effective, especially on large tanks, and is seldom used nowadays for RAF aircraft. On the other hand, forced air ventilation, which involves blowing a large volume of warm, low pressure air into the tank and forcing vapour out through access holes, is highly effective for all sizes of fuel tanks and can ventilate a small tank to a safe level in as little as 30 minutes. Once an initial safe level is reached, personnel enter the vented area to mop up fuel puddles and commence the repair.

14. What ever the method employed, the major problem in venting fuel tanks has always been the equipment available in the RAF. Heaters and air blowers are mostly elderly and are driven by petrol or diesel engines, which must be positioned well away from aircraft. As a result, the long hoses required to reach the aircraft allow the air to cool whilst reducing the flow quite significantly. As the majority of our front-line aircraft are now based in Hardened Aircraft Shelters (HASs), where space is at a premium, we are currently introducing a new, universal fuel tank repair trolley, which has a multi-task capability and can be operated in the HAS environment as close to the aircraft as necessary. This new equipment represents a considerable improvement in our fuel tank repair capability at all levels of maintenance.

REPAIR

15. Of all the stages in repairing a fuel leak, preparation, including removing the old sealant, preparing the surfaces for resealing and mixing the new sealant, is probably both the most critical and the most difficult to complete successfully. To begin with, all traces of loose, damaged or contaminated sealant must be removed with minimal damage to the substrate, and scrapers used for this purpose must be made of a plastic or wood. Removing sealant from most aircraft tanks is a laborious process exacerbated by access problems, lack of light, an uncomfortable environment and the inevitable pressure to get the job done quickly. Unfortunately, at present there is no quick way of removing old sealant without risking injury to the operator or damage to the substrate, and we are still reliant on skilled manpower and basic hand tools.

16. Once the old sealant has been removed, the surface must be prepared to receive the new sealant. At present, most sealants are used directly onto coated aluminium, and a strong, continuous bond between the coating and the aluminium is essential for an effective seal. We have found that the best way to achieve a good bond is to first clean the surface with a detergent cleaner to remove most contaminants, followed by an organic solvent cleaner such as MEK or Toluene. Once cleaned in this manner, we allow 30 minutes to elapse for the solvent to evaporate and the surface to stabilise at ambient temperature before applying any further surface treatment or sealant. Where primed substrates are to be resealed, we use the same cleaning process before re-priming or refreshing the primer and re-clean immediately before resealing.

17. It is extremely important to thoroughly mix sealants before application. Traditionally, most sealants used in the RAF have been supplied as a two-part mix; a tin of sealant and a small tub or bottle of activator. Mixing these parts is generally a wasteful process which often results in the sealant being heavily aerated and contaminated with dirt, oil or water before application. However, we have recently introduced the SEMKIT into the RAF, and a wide range of polysulphide sealants are now available in this form of package. The semkit comprises a plastic syringe, the body of which contains the sealant, and the stem of which

contains the activator. By injecting the activator without separating the package and mixing and applying the sealant from a sealed unit, the risks of aeration and contamination is negated, whilst sealant can be injected directly onto the substrate as a fillet, interfav or overcoat.

18. The final properties of any sealant are influenced by the quality of surface preparation and the thoroughness of the final cure. The working life of most sealants is designed to give the operator time to mix and apply the sealant and in general, the longer the working life the longer the final cure time. As the cure time is the time taken for the sealant to achieve a specified performance, the user is primarily responsible for the quality of the final seal by the care with which he control_ the curing time and environment of the sealant during the curing cycle. It is significant that after inadequate preparation, incomplete curing of the sealant is the most common cause of failed repairs on RAF aircraft.

SUGGESTED IMPROVEMENTS

19. We feel there are numerous areas where improvements can be made to the way integral fuel tanks are repaired with the RAF. To begin with, there are 2 advanced viewing techniques which we believe could be applied to fuel tank leak testing:

a. Real-Time X-Ray. Real time X-ray techniques are currently being developed for use in non-destructive testing. The procedures is not yet sufficiently developed for use in detecting fuel leaks, but it may offer a method of following 'tracking' leaks in complex structures by introducing a marker agent into the fuel, pressurising the tank, draining and scanning the seams for track paths.

b. Thermal Imaging. The use of thermal imaging in the RAF is less well developed but is currently used by British Airways to locate trapped water in aircraft structures. This is achieved by scanning likely areas with a thermal imaging camera soon after the aircraft has landed from a high altitude flight; any trapped water shows as a cold spot in the structure. In a similar manner, fuel leak paths may be detectable by the temperature difference between the fuel and the surrounding structure. Both of the viewing aids are at an early stage of development and their use for fuel leak detection has yet to be fully investigated by the CSDE.

20. The major problem in venting fuel tanks is the lack of suitable ground equipment. The new universal fuel tank repair trolley currently being introduced offers a great improvement for the future, although we have a need for a range of simpler portable ventilators for a variety of tasks including simple tank repairs.

21. Probably the most vital element in effective fuel tank repair is the attention to detail paid to preparation, especially removing old sealant and preparing the substrate for resealing. No matter how good the sealant, it will not adhere properly to a substrate which is contaminated with moisture, oil or dust. As detecting disbonded areas within a sealed joint is virtually impossible at present, the operator applying the sealant is solely responsible for the quality of the seal. At present, fuel tank repair procedures supplied to the RAF in aircraft maintenance manuals vary from comprehensive procedures and techniques in a single aircraft publication, to a collection of cross-referred sentences or paragraphs spread over several manuals. As our front-line tradesmen rarely have specialist training in fuel tank repair techniques, we require repair information and procedures supplied by aircraft manufacturers to be clear, concise and comprehensive from the outset.

22. Before adequate information can be provided in repair manuals, we need to

look at new equipment and methods of removing old sealants, as any improvements in this area would be of benefit. We understand that our American colleagues are experimenting with sealant removal by blasting with dry ice pellets, and we await results of these trials with interest. In addition, as plastic media stripping (PMS), which use plastic media propelled by an air stream, is currently being trialled in the RAF for the removal of surface finish from components, the system could perhaps be adapted for sealant removal, although the debris created may be a problem. We have even considered chemical strippers, but they are difficult to control properly, and the health and safety problems are insurmountable. Outside the military environment, we understand that British Airways have been using an ultra-fine, high pressure water jet to cut off old sealant, but again we believe that health and safety consideration would preclude its use in the complex, confined spaces in our tanks. Finally, the pre-conditioning of fuel tanks prior to resealing is also worth considering, as a standard temperature and humidity of 25°C and 55% RH should be maintained as far as possible for optimum adhesion of the sealant. Unfortunately, these conditions are rarely met on an RAF flight line, and the leak is inevitably either temporarily plugged, deferred until later or repaired in unsuitable conditions, generally unsuccessfully.

23. Looking at the sealants we use, we know that the sealant manufacturers are constantly striving to improve their products, and some new products, including a low temperature, fast curing sealant used in conjunction with a dedicated primer, are currently undergoing tests at our Directorate of Quality Assurance at Woolwich. In the wider field we are aware of research by McDonnell Douglas into the spraying of an advanced sprayable elastomer which forms a membrane over the internal surfaces of the fuel tanks and we look forward to studying their findings. However, what we really need is a sealant which offers a reduced curing time at lower temperatures, coupled with the ability to adhere to a surface which has not been prepared to the highest standard. If such a product could be found, it would provide us with the ideal solution to the whole problem of surface preparation and sealant application. In the short-term however, we would like to see both existing and new sealants made available in 2 contrasting colours, which would assist both operators and supervisors in ensuring that layered or overcoated sealants are correctly applied.

24. In the training field, we have begun to improve both the amount and type of training given to our maintenance personnel. Sealant manufacturers representatives we have spoken with are extremely keen to support a training programme for both the RAF and industry, and are willing to provide information on the correct use and selection of sealants and to give practical demonstrations. In addition, they are willing to visit their customers on a regular basis to give expert technical advice on specific fuel leaks at the aircraft. As they are willing to offer these facilities to repairers, surely they would also be willing to co-operate with the aircraft manufacturers at both the design and assembly stages of a project, both to provide advice on product selection and use, and to ensure that their product development programmes are directed towards user requirements.

DESIGN

25. In addition to our suggestions that sealant manufacturers should tailor their products to meet user requirements, we believe that aircraft designers should take account of the likely operating and repair environments of their products as well as future trends in health and safety regulations which may well dictate repair procedures. As the majority of problems currently associated with integral fuel tank repairs start at the design stage, we believe that careful consideration should be given to all factors of aircraft design which may affect fuel tank sealing. Considerations such as sealant selection, the manufacture, construction, positioning of and access to fuel tanks and their associated components, the likelihood of high temperatures in adjacent areas, the role of the aircraft, and load levels in highly stressed areas all affect sealant performance and repairability in the long-term. A great many fuel leaks occur in the original sealant at an early stage in aircraft life, and whilst these may be the result of poor workmanship or conditions on production lines, they may equally result from poor design. For example, the awkward shapes in some Harrier aircraft fuel tanks, where a conduit passes through the tank wall adjacent to both a structure and a

skin joint, inevitably require resealing at a very early stage in aircraft life, and may never be successfully sealed. In addition, once a leaks has occurred the major problem for the repairer may well be a question of access, and in general, the smaller the aircraft the smaller the tank and the larger the access problem. Whilst we appreciate that fuel tanks are often placed, of necessity, into cramped and relatively inaccessible areas, the poorer the access to such tanks, the more likely it is that they will leak, and the more difficult it will be to effect a high quality, long lasting repair. Adequate access, coupled with minimum disruption to other system and components, makes the task of both builder and repairer that much easier. Access panels need to be big enough to allow a tradesman to reach either the remotest part of a tank or another access panel. and should also have a facility for introducing an inspection source, such as the Videoprobe 2000. Finally fuel tanks should have as few components as possible fastened to their boundary walls in order to minimise flexing and reduce the number of fasteners in the tank skins, and should be designed with smooth contours and a minimum of sharp corners.

CONCLUSION

26. The Royal Air Force has some way to go before we can complete all our repairs effectively and at minimum cost. However, recent improvements in training and equipment, together with a greater awareness of new and improved sealants and repair techniques have begun to show benefits in terms of reduced aircraft downtime and more successful repairs. Nonetheless, our development work is still at an early stage in many areas, and we have a great deal still to do in perfecting leak detection methods and in cutting the manhour cost of removing old sealants. In this area in particular, we are hampered by the poor design of many of our aircraft, as well as a lack of more environmentally tolerant sealants. With the increase in contractural requirements for new aircraft to meet specified reliability and maintainability (R&M) targets, designers must develop an awareness of the R&M implications of fuel leaks, both in terms of failure rate and in their effect on aircraft downtimes. In this way, fuel tank design will begin to be given a higher priority and our next generation of aircraft may be able to spend more time where they belong, in the air!

THE EFFECT OF PRIMER AGE ON ADHESION OF POLYSULPHIDE SEALANT

by

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SUMMARY

Sealants used in aircraft integral fuel tanks must adhere well to primed substrate surfaces. In this paper the adhesion of polysulphide sealant (PR1422) to primed aluminium alloy surfaces of different primer age has been studied with respect to the effect on lap-shear strength of ageing in fuel at 100°C. Freshly primed surfaces, 1 day old, have been compared with a range of older primed surfaces.

With a 'standard' epoxy chromate primer, primer age has a very marked effect on lap-shear strength, the value after 10 days in fuel (Avtur) at 100°C being a factor of 2 less for 2-20 week old primed specimens as compared to a freshly primed one. In contrast, similar studies using three 'tolerant' epoxy chromate primers indicate that primer age has much less effect on the adhesion of PR1422 sealant to these primers, lap shear strengths after ageing in fuel at 100°C showing much less dependence on primer age.

These results would appear to be very relevant to both repair and manufacture of integral fuel tanks.

1 INTRODUCTION

The most widely used of aircraft sealants are based on liquid polysulphide polymers: these afford materials that can be cured at room temperature, have good elastomeric properties over a wide range of temperature and give acceptable levels of fuel and water resistance. One of the most demanding applications is that of sealing aircraft integral fuel tanks where the sealant is used to fill gaps in interfays and for the formation of fillets. In general the gaps to be filled are not constant but vary due to vibrations in the aircraft structure: to accommodate this movement without breaking the seal it is vital that the sealant is a good elastomer *and* also adheres well to substrate surfaces. The latter have invariably undergone a surface pretreatment schedule which includes coating surfaces with an appropriate primer - for UK military aircraft this will be an epoxy chromate paint, the principal function of this being to protect aluminium alloy surfaces from the onset of corrosion.

In recent years increasing emphasis has been placed on the problems of repairing leaks in integral fuel tanks: these may be due to a range of sealant problems such as cracking, porosity and the loss of adhesion between the sealant and the primed tank surface. Much work has been done in the past on the effect of changes in polysulphide type, catalyst, etc, on the properties of polysulphide sealants, including adhesion of sealant to substrate, but little has been done on the effect of surface primer on the latter property. Some years ago Usmani and co-workers[1,2] noted that, where fuel tanks were primed with a polyurethane coating, leaks in integral tanks could not be repaired directly by replacing old sealant with new, because the latter would not adhere well to the aged polyurethane primer. They studied the chemical factors responsible for this effect and investigated possible surface pretreatments to 'reactivate' the polyurethane primed surface.

The experiments described in the present study involve an investigation of the effect of ageing in Avtur at 100°C on the adhesion of polysulphide sealant (PR1422) to epoxychromate primed aluminium alloy surfaces of different primer age (*ie* time since surface primed). Initial studies concentrated on standard epoxychromate primed surfaces but these were later widened to include three 'tolerant' epoxychromate primers: adhesion was measured via lap-shear tests on appropriate joints.

2 EXPERIMENTAL

2.1 Materials

The sealant used (PR1422A2) was a brushing grade compound based on a dichromate cured, thiol terminated, polysulphide polymer. The standard epoxychromate and three 'tolerant' epoxychromate primers tested all met specification DTD5567A; the 'tolerant' primers also met other specifications. The aviation fuel used for ageing tests was NATO F-34 (Avtur) and the aluminium sheet used for lap-shear specimens was L163 alloy (1.5 mm thick).

2.2 Procedure

A flow chart for the preparation of test specimens is given at Fig 1.

Aluminium alloy coupons (Fig 2a) were pickled to DEF STAN 03-02, method O, then anodised to DEF STAN 151/2; priming with appropriate primer followed within 24 hours of anodising. Primed coupons were stored for different periods of time (see Fig 1), the storage conditions being *either* on a laboratory bench with no protection *or* coupons individually sealed in a polythene bag and stored in a desiccator. There were some variations in storage times due to holiday periods.

After appropriate storage times lap-shear specimens were prepared as follows:

(a) Polysulphide sealant was carefully prepared to give a uniform, air-free blend.

(b) Primed and appropriately aged alloy coupons were solvent wiped with methylethylketone and allowed to dry.

(c) One half of the top surface of each of two coupons was coated with sealant and the two then bolted together immediately. Excess sealant was squeezed out as the bolts were tightened to a torque setting of 5.1 N m. The nut and bolt heads on the lap-shear specimen so prepared (Fig 2b) were overcoated with sealant and the specimen left to cure on a bench for 42 days at 20°C.

The lap-shear specimens so prepared simulate an interfay joint as used in aircraft construction. It should be noted from Fig 1 that the lap-shear specimens for the investigation of a particular primer were all prepared on the same day using the same batch of sealant: this was done in order to minimise experimental variability.

When the sealant was fully cured, lap-shear specimens were immersed in Avtur at 100°C for differing periods of time. During ageing fuel was changed every 4 days in order to reduce the build-up of fuel oxidation products and materials leached from primed surfaces, both of which might adversely affect the sealant: fuel was heated to 100°C prior to changing to keep the immersion temperature constant and to prevent specimens from being subjected to thermal shock.

After appropriate periods of ageing, specimens were removed and stored in Avtur at room temperature for 24 hours. Following removal of the nut/bolt pairs from specimens, lap-shear strength measurements were made with an Instron machine using a cross-head speed of 10 mm/min: each result is the median of three replicates.

3 RESULTS AND DISCUSSION

The results of lap-shear tests on specimens prepared with the standard and the three tolerant epoxychromate primers are given in Tables 1 to 4 and are illustrated graphically in Figs 3 to 7. It should be noted that where results for different primer ageing times lie close together, a band is shown rather than individual curves in order to simplify presentation. Within a particular band of results there was no progressive change as primer age increased; results tended to be scattered within the band.

Considering first the standard epoxychromate primer, the results for bench conditioned specimens are given in Table 1(a) and Fig 3. Clearly, after 10-20 days ageing in Avtur at 100°C, the lap-shear strength of the primed alloy/sealant joint is markedly lower for specimens where the primer age was 14 days or more than for fresh primer (1 day line): the joint strength has dropped by a factor of about 2 after 15 days ageing in fuel. After the same ageing in Avtur the 7-day storage line is intermediate between that for freshly-primed alloy and the main band of results, suggesting that in this particular case any effect of storage is incomplete at this point. The 84 day result also differs from the others: the reasons for this are not known. The results for desiccator conditioned samples are given in Table 1(b) and Fig 4: these are very similar to those for the bench conditioned specimens except that the 7 day storage line lies within the main band.

The results for the first 'tolerant' primer are given in Table 2 and illustrated graphically in Fig 5; they are clearly very different to the standard primer. In this case the joint strength for fresh primer (1 day line) lies in the lower half of a band which covers all other conditioning times except the 84 day one: the line for the latter lies marginally above the upper edge of the band. Increase in primer age clearly causes no deterioration in primed alloy/sealant joint strength in this case: it may even result in a marginal improvement. The results for the desiccator conditioned samples were essentially the same as the bench-conditioned ones.

The second 'tolerant' primer results are given in Table 3 and at Fig 6. The curve for the 1-day (fresh) primed specimen lies on the upper edge of a relatively narrow band which includes all other results except the 84-day one. Thus, primer age has only a small effect with this primer. The results for the desiccator conditioned samples were essentially within the band for the bench conditioned ones except for the 84-day result. The latter line lies very close to that for the 84-day bench conditioned sample and well above the band for other results: no explanation can be offered for this.

The results for the third 'tolerant' primer are given in Table 4 and at Fig 7. Here, the curve for the freshly primed (1-day) specimen lies below the band covering the aged primer samples: ageing would therefore appear to be advantageous with this primer in contrast to the standard one. Again the desiccator conditioned samples are essentially the same as the bench conditioned items and the 84-day result differs as before.

In general, therefore, increase of primer age does not cause the marked lowering in adhesion of PR1422 sealant to alloy surfaces primed with 'tolerant' primers that it does with standard primer when lap-shear specimens are aged in Avtur at 100°C. However, it can clearly be seen that in all cases ageing in Avtur at 100°C causes a very marked drop in lap-shear strength, the reduction varying significantly between the primers tested. Thus, whilst the initial lap-shear strength of sealant/primed alloy joints for all the primers tested was in the range 2 to 2.5 MPa, lap-shear strengths after ageing in Avtur for 15 days at 100°C are very different both for freshly primed samples and for the mid-band position: these results are shown in Table 5. Clearly, from the tests done in this study the first 'tolerant' primer gives the best result. Also, although storage may improve the result for the third 'tolerant' primer it cannot be considered as being significantly better than the standard primer.

With respect to the mode of failure of lap-shear specimens it was found that, prior to ageing in Avtur at 100°C, both standard and 'tolerant' primer treated joints invariably failed cohesively. Ageing in Avtur at 100°C led to an increasing proportion of interfacial failure with all the primers tested, but it was not possible to correlate reliably the extent of this with ageing time because of experimental difficulties. One other point to emerge is that the storage conditions for primed samples have virtually no effect on the results: primed aluminium alloy coupons that were carefully bagged and then stored in a desiccator gave the same results as those stored, without protection, on a laboratory bench.

One point that must be stressed is that only one batch of each primer used was tested: thus, the results give no indication of the possible scale of batch-to-batch variations. Apart from this

limitation the results would appear to have considerable importance with respect to both the construction and the repair of integral fuel tanks. From the construction aspect, discussions with manufacturers indicate that not all sealant/primed alloy joints are made with freshly primed surfaces. Thus, the halving of the lap-shear strength (Table 5 mid-primer age band: freshly primed) that can occur with joints involving non-fresh standard primer surfaces may result in problems during service life. Although the 15 days ageing in fuel at 100°C is not readily equated to a precise in-service period, if it is assumed that reaction rate doubles for every 10°C rise in temperature (a widely used but only approximate guide), then the 15 day ageing period would be approximately equal to 10 years in fuel at ambient temperature. Sealant adhesion problems may therefore be significantly more likely to occur about halfway through an aircraft's intended service life where non-fresh standard primer surfaces were involved in seal formation during construction. The use of the best available 'tolerant' primer at the construction stage could significantly reduce this loss of adhesion between sealant and primed alloy and increase the likelihood of integral tanks remaining leak-free. Equally, where repairs are required, if tolerant primer has been used during construction, the repair sealant will adhere better giving an increased chance of a successful repair.

4 CONCLUSIONS

(1) For 'tolerant' epoxychromate primed substrates, the age of the primed surface has little effect on the lap-shear strength of sealant/substrate joints in contrast to standard epoxychromate primed substrates where this is a significant effect.

(2) Storage conditions of primed coupons (open bench or bagged in desiccator) have virtually no effect on sealant/substrate joint strength.

(3) The use of the best available 'tolerant' primer during aircraft construction could reduce integral fuel tank leaks during service.

(4) When fuel leaks occur, the use of 'tolerant' primers during construction will aid repair.

Table 1

STANDARD PRIMER - EFFECT OF PRIMER AGE/IMMERSION IN AVTUR AT 100°C ON LAP-SHEAR STRENGTH

a. Bench conditioned samples

Storage time (days) → / Ageing in Avtur (days) ↓	1	7	14	28	42	84	140
	Lap-shear strength (MPa)						
0	2.12	2.05	2.35	2.18	2.05	2.24	2.38
2	1.57	1.64	1.95	1.88	1.53	1.26	1.71
4	1.37	1.61	1.60	1.95	1.46	0.70	1.06
8	1.27	1.24	0.61	1.13	0.59	0.48	0.73
16	0.98	0.85	0.63	0.55	0.55	0.19	0.34
32	1.19	0.56	0.39	0.69	0.61	0.18	0.72

b. Desiccator conditioned samples

Storage time (days) → / Ageing in Avtur (days) ↓	1	7	14	28	42	84	140
	Lap-shear strength (MPa)						
0	2.12	2.10	2.37	2.30	2.22	2.32	2.47
2	1.57	1.77	1.72	1.91	1.71	1.01	1.74
4	1.37	1.34	1.18	1.61	1.05	0.59	1.15
8	1.27	0.79	0.53	1.10	0.61	0.34	0.69
16	0.98	0.56	0.47	0.57	0.46	0.26	0.54
32	1.19	0.65	0.67	0.50	0.34	0.54	0.74

Table 2

FIRST TOLERANT PRIMER - EFFECT OF PRIMER AGE/IMMERSION IN AVTUR AT 100°C ON LAP-SHEAR STRENGTH

a. Bench conditioned samples

Storage time (days) → / Ageing in Avtur (days) ↓	1	7	14	28	49	84	147
	Lap-shear strength (MPa)						
0	2.46	2.24	2.30	1.90	2.14	2.45	2.40
2	1.53	1.64	1.68	1.55	1.77	1.76	2.13
4	1.48	1.58	1.52	1.40	1.52	1.63	1.89
8	1.11	1.34	1.22	1.05	1.31	1.55	1.53
16	1.01	1.18	1.09	0.92	1.19	1.42	1.39
32	0.91	1.09	0.95	0.79	0.98	1.18	1.05

b. Desiccator conditioned samples

Storage time (days) → / Ageing in Avtur (days) ↓	1	7	14	28	49	84	147
	Lap-shear strength (MPa)						
0	2.46	1.96	2.18	2.36	2.45	2.38	2.54
2	1.53	1.71	2.01	1.60	1.89	1.86	2.10
4	1.48	1.56	1.75	1.41	1.82	1.92	1.87
8	1.11	1.36	1.30	1.08	1.51	1.62	1.48
16	1.01	1.32	0.98	0.86	1.25	1.46	1.17
32	0.91	1.01	0.92	0.68	1.07	1.17	0.99

Table 3

SECOND TOLERANT PRIMER - EFFECT OF PRIMER AGE/IMMERSION IN AVTUR AT 100°C ON LAP-SHEAR STRENGTH

a. Bench conditioned samples

Storage time (days) → / Ageing in Avtur (days) ↓	1	7	14	21	42	84	140
	Lap-shear strength (MPa)						
0	2.02	2.11	2.05	1.91	2.09	2.03	2.23
2	1.74	1.76	1.86	1.67	1.78	1.67	1.86
4	1.45	1.43	1.54	1.58	1.55	1.78	1.59
8	1.15	1.01	1.05	0.97	0.94	1.61	1.00
16	0.87	0.66	0.64	0.77	0.67	1.26	0.86
32	0.66	0.37	0.62	0.62	0.63	0.99	0.56

b. Desiccator conditioned samples

Storage time (days) → / Ageing in Avtur (days) ↓	1	7	14	21	42	84	140
	Lap-shear strength (MPa)						
0	2.02	2.08	2.21	1.94	2.22	2.13	2.12
2	1.74	1.90	1.81	1.67	1.68	1.86	1.96
4	1.45	1.65	1.51	1.30	1.40	1.79	1.48
9	1.15	0.97	0.96	1.01	1.00	1.44	1.04
16	0.87	0.68	0.70	0.65	0.70	1.32	0.79
32	0.66	0.53	0.60	0.65	0.65	1.02	0.60

Table 4

THIRD TOLERANT PRIMER - EFFECT OF PRIMER AGE/IMMERSION IN AVTUR AT 100°C ON LAP-SHEAR STRENGTH

a. Bench conditioned samples

Storage time (days) → / Aging in Avtur (days) ↓	1	7	14	28	42	84	140
	Lap-shear strength (MPa)						
0	2.27	2.46	2.66	2.50	2.69	2.49	2.50
2	1.30	1.77	1.59	2.05	2.07	2.17	2.04
4	0.65	1.11	0.80	1.43	1.31	1.56	1.44
8	0.52	0.63	0.67	0.88	0.98	1.29	1.07
16	0.43	0.52	0.54	0.70	0.71	1.07	0.81
32	0.60	0.86	0.73	1.07	0.91	1.62	1.15

b. Desiccator conditional samples

Storage time (days) → / Ageing in Avtur (days) ↓	1	7	14	28	42	84	140
	Lap-shear strength (MPa)						
0	2.27	2.71	2.64	2.43	2.47	2.37	2.33
2	1.30	1.81	1.58	2.00	1.67	1.90	1.74
4	0.67	1.09	0.80	1.18	1.16	1.27	1.36
8	0.52	0.71	0.62	0.92	0.68	1.07	0.93
16	0.43	0.52	0.51	0.68	0.54	0.85	0.74
32	0.60	0.80	0.63	0.95	0.78	1.20	0.92

Table 5

COMPARISON OF PRIMERS AND PRIMER AGE AFTER AGEING FOR 15 DAYS IN AVTUR AT 100°C: LAP-SHEAR STRENGTH (MPa)

Primer conditioning	Standard primer	First tolerant primer	Second tolerant primer	Third tolerant primer
Freshly primed (1 day)	1.0	1.0	0.9	0.45
Mid-primer age band	0.5	1.15	0.8	0.7

Prior to ageing in Avtur all primers gave joints with initial lap-shear strength of 2 to 2.5 MPa.

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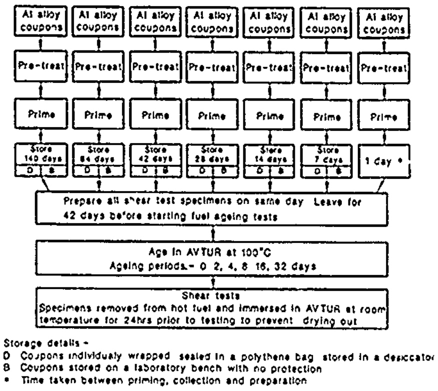

Fig 1 Flow chart for the preparation of test specimens

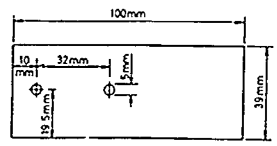

Fig 2a Al-alloy coupon

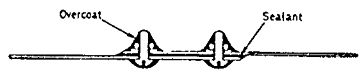

Fig 2b Lap - shear specimen - cross-section

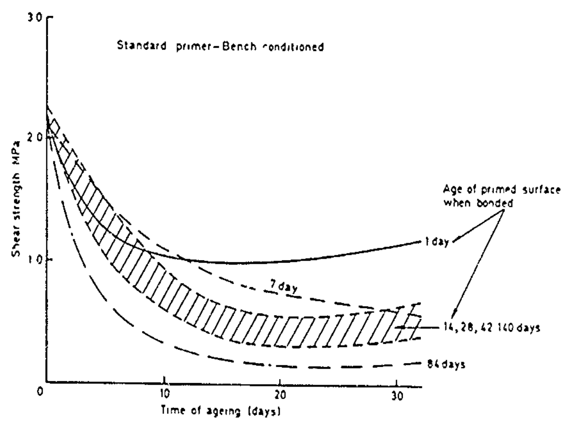

Fig 3 Effect on shear strength of ageing joints in AVTUR at 100°C

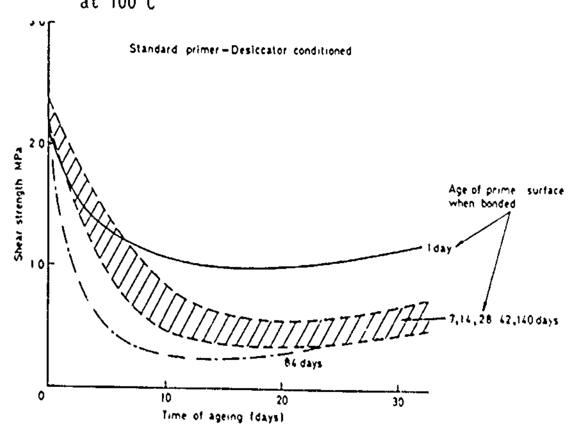

Fig 4 Effect on shear strength of ageing joints in AVTUR at 100°C

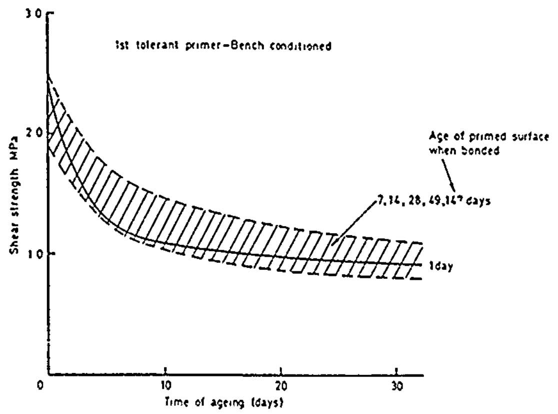

Fig 5 Effect on shear strength of ageing joints in AVTUR at 100°C

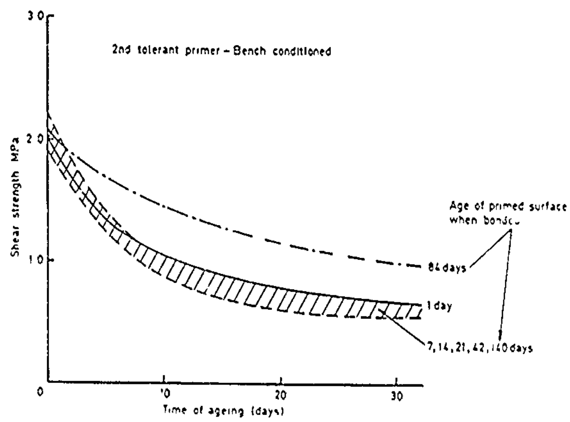

Fig 6 Effect on shear strength of ageing joints in AVTUR at 100°C

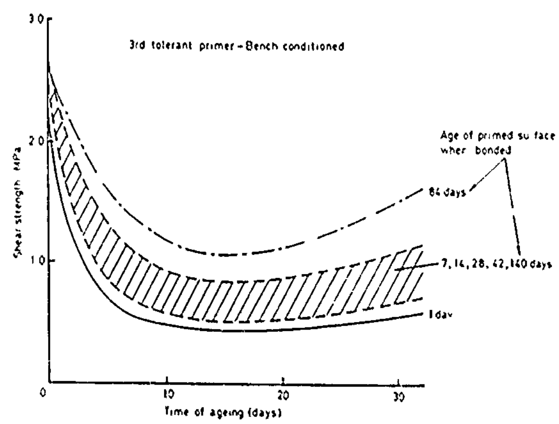

Fig 7 Effect on shear strength of ageing joints in AVTUR at 100°C

IMPROVED PERFORMANCE POLYSULFIDE BASED SEALANT

by

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At Products Research and Chemical Corporation we have recently discovered that low viscosity mercaptan terminated polymers which exhibit application and performance properties superior to their precursor materials can be obtained by chemical modification of Thiokol LP polymers. For example, these chemically modified Thiokol LP polymers, known as Permapol* P-5 polymers, can be formulated and cured using similar methods as LP polymers to give elastomeric materials which, compared to the same LP polymer based materials, exhibit:

- Superior ozone and UV radiation resistance.
- Higher physical properties.
- Better fuel resistance.
- Higher temperature resistance.
- Greater compatibility with traditional plasticizers.
- Better adhesion to many substrates after exposure to liquids such as aromatic hydrocarbon containing fuels.
- Better resistance to permeability of inert gases and fuel vapors.

The present paper describes the properties and uses, of this new class of polymers, in some sealant formulations as compared to their precursor materials, the Thiokol LP polymers.

Sealant Definition:

Elastomeric material to provide environmental isolation, and to join two surfaces together for the purpose of load transfer.

Sealant Property Requirement:

1. General Properties–
   a. Properties of the uncured system.
   b. Properties of the cured system.
2. Specification document and specialty sealants–
   a. Government specifications.
      Mil-S-8802
      Mil-S-83430
      Mil-S-81733
   b. Industry specification (specialty sealants)

*Trademark of Products Research & Chemical Corporation

Sealant Ingredients:

1. Base polymer.
2. Filler.
3. Accelerator.
4. Adhesion promoter.
5. Pigment.
6. Plasticizer.

Sealant Application:

1. Moisture barrier.
2. Fuel/solvent barrier.
3. Vibration/shock attenuator.
4. Thermal insulation.
5. Electrical insulator.
6. Electrical conductor.
7. Aerodynamic smoother.
8. Void, groove/channel filler.
9. Corrosion inhibitor.
10. Adhesives.
11. Field repair.

Application Methods:

1. Brushing.
2. Extrusion.
3. Faying surface.
4. Spraying.

Permapol P-5 Polymers

Permapol P-5 polymers are produced by reaction of Thiokol LP polymers with a dithiol in the presence of a suitable catalyst. The chemical structure of Thiokol LP polymer and the reaction involved is represented by the equation in Figure 1.

As can be seen, the product of this reaction is a mixture of polymers which consists of a lower molecular weight moiety identical in structure to the starting polymer and another moiety whose structure incorporates the chemically modifying dithiol molecule. This mixture is designated as Permapol P-5 polymer.

The Permapol P-5 polymers obtained with DMDS as modifier exhibit several other highly desirable characteristics which make them preferred candidate materials for high performance sealants, adhesives and coatings as compared to LP polymers. For example, because of their low viscosity, sealants and coatings can be formulated with little or no solvent, an extremely desirable property in view of EPA regulations concerning volatile organic concentration (VOC). Furthermore, these sealants exhibit little or no shrinkage on curing a property which is particularly desirable in insulating glass sealants where the sealant shrinkage may result in breakage of glass.

A comparison of physical properties, thermal resistance and fuel vapor permeability of Thiokol LP and Permapol P-5 based adhesives and sealants was carried out. The results are presented in the following sections.

Permapol P-5 Polymer
Chemical Modification Reaction

$$HS\text{-}[CH_2\text{-}CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2\text{-}CH_2\text{-}(S)_x]_n CH_2\text{-}CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2\text{-}CH_2\text{-}SH \quad + \quad HS\text{-}R\text{-}SH$$

LP POLYMER DITHIOL

$$\xrightarrow{\text{Catalyst}} HS\text{-}[CH_2\text{-}CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2\text{-}CH_2\text{-}(S)_x]_m CH_2\text{-}CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2\text{-}CH_2\text{-}SH$$

LP POLYMER

+

$$HS\text{-}[CH_2\text{-}CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2\text{-}CH_2\text{-}(S)_x]_{n\text{-}m} R\text{-}SH$$

DITHIOL MODIFIED LP POLYMER

x is the sulfur rank of the polymers with the value of 2 to 3
n is 5 to 25
m is 0 to 24

Figure 1

Thermal Stability

Thermal stability of Permapol P-5 polymers was studied in a simple adhesive formulation. LP-3, a Thiokol polymer, with viscosity comparable to Permapol P-5 polymers, was included as a control. Table 1 presents the formulations and the effect of heat exposure on these formulations as measured in loss of hardness after exposure.

The LP-3 based formulation shows a faster drop of hardness as compared to any Permapol P-5 based material.

Table 1

Thermal Stability of Permapol P-5 Based Adhesive Formulations

	I	II
Thiokol LP-3	100	-
Permapol P-5 (LP-2 Modified with DMDS)	-	100
Permapol P-5 (LP-2 Modified with ED)	-	-
Permapol P-5 (LP-2 Modified with DMDO)	-	-
DMP-30* 2,4,6-tri(dimethylaminoethyl) Phenol	10	10
Epoxy Resin (Epon 828)**	100	100
HARDNESS, SHORE D		
Initial	77	77
After 12 weeks at 82°C	40	55

*Trademark of Rohmand Haas Company
**Trademark of Shell Chemical Company

Thermal Stability

Figure 2 shows a comparison of weight loss between Permapol P-5 and Thiokol LP-12C.

As is shown, Thiokol LP-12C shows a weight loss of 24% after 10 hours at 182°C, while Permapol P-5 has only 5% weight loss at the same time and temperature.

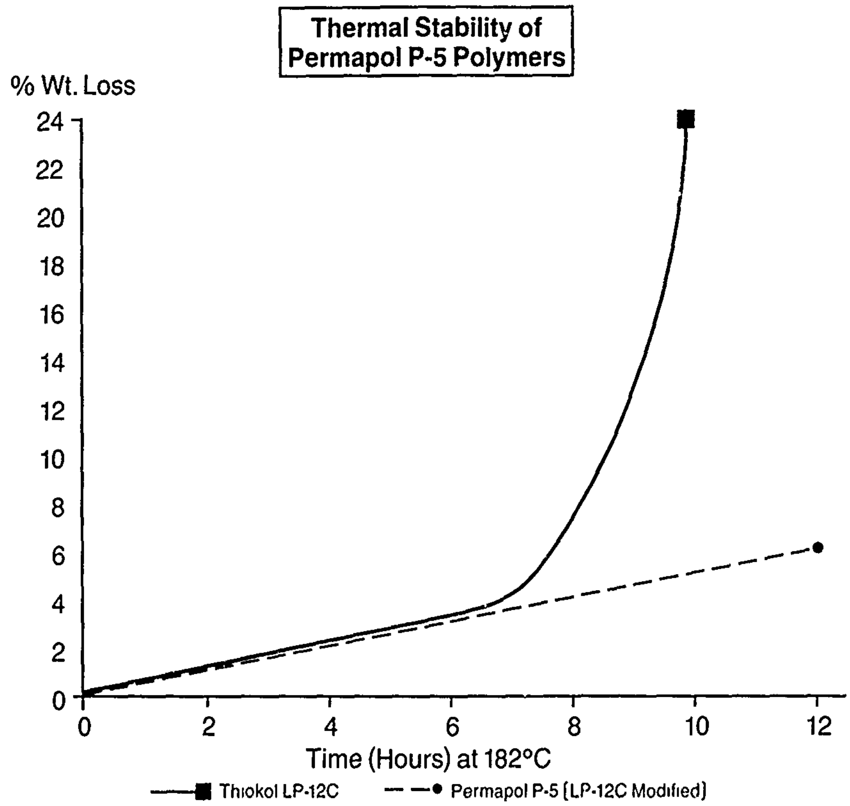


Figure 2

Physical Properties

Two identical sealant formulations were prepared using (1) a blend of LP-31 and LP-2 in the ratio 2:1 and (2) a blend of P-5 polymers derived from LP-31 and LP-2 in the same ratio. These Permapol P-5 polymers used DMDS as the modifying dithiol. A description of these formulations is given in Table 2.

The base and accelerator were mixed in a ratio of 100 to 10 (by weight) and cast into 0.125 inch centimeter thick sheets. After curing, their physical properties were determined. The results thus obtained are shown.

Table 2

Typical Sealant Formulations

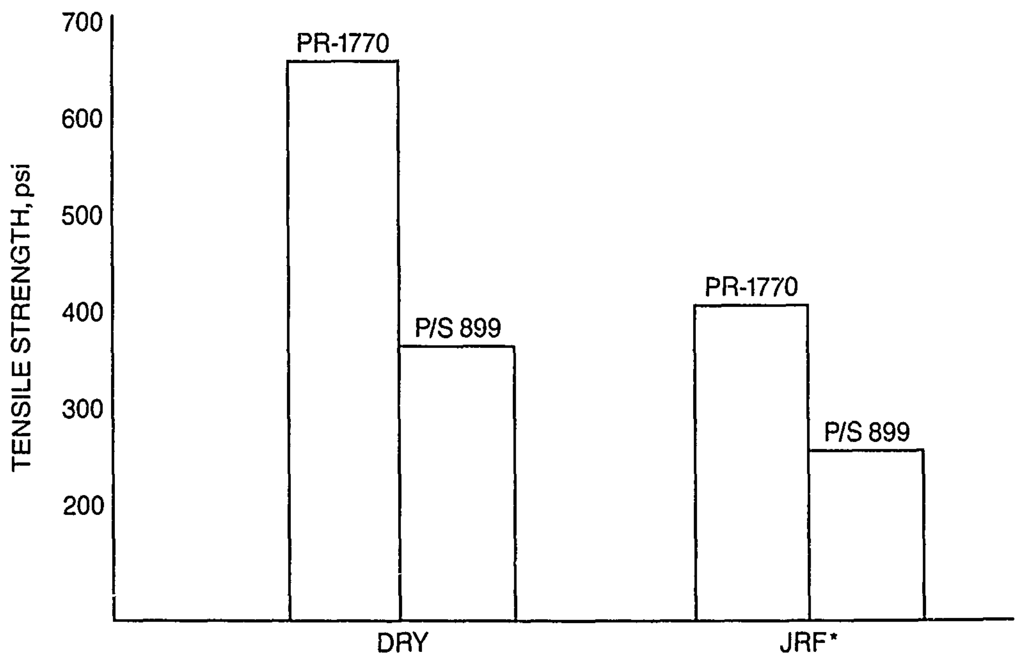
Base	I	II
Thiokol LP Polymer Blend	55	–
Permapol P-5 Polymer Blend	–	55
Filler	33	33
Phenolic Adhesion Promoter	7	7
Titanium Dioxide	4	4
Catalyst	1	1
Accelerator		
Manganese Dioxide	5	5
Hydrogenated Terphenyl (HB-40)*	5	5
Accelerator to base ratio is 1:10		

*Trademark of Monsanto Chemical Company

Physical Properties of LP and Permapol P-5 Polymer Based Sealants

Tensile Strength, (psi)

	I (Thiokol LP)	II (Permapol P-5)
Initial	380	680
After 14 days @ 60°C in Jet Reference Fluid	250	430
After 2 hours @ 204°C	reverted to liquid	150



*Jet Reference Fuel Type VII (Material immersed for 14 days @ 140°F.)

Elongation at Break, %

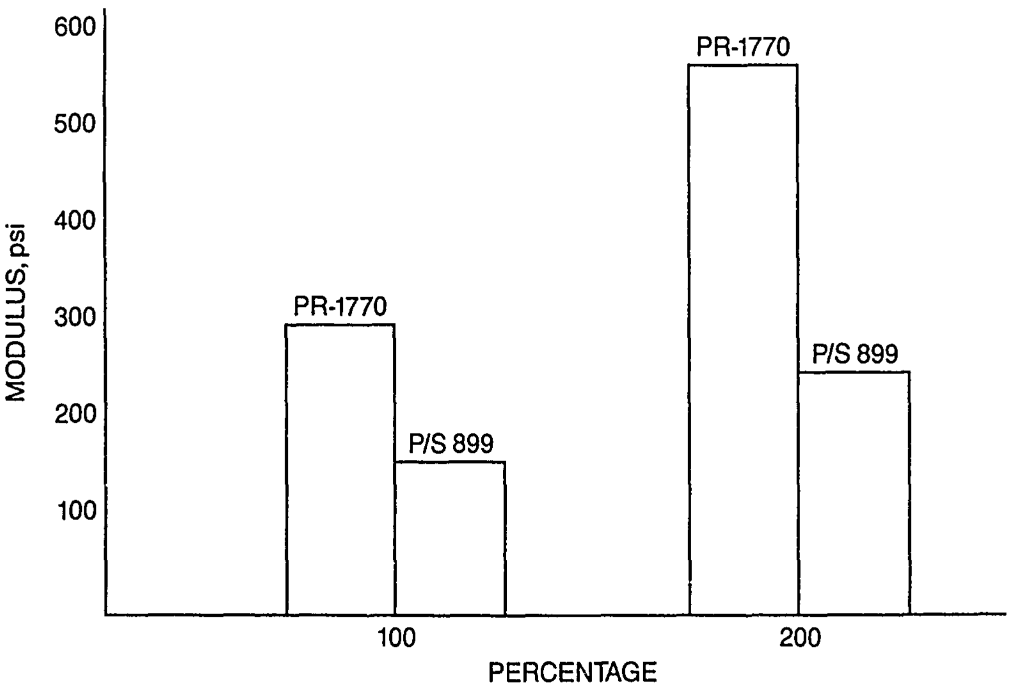
	I (Thiokol LP)	II (Permapol P-5)
Initial	300	270
14 days @ 60°C in Jet Reference Fluid	300	350
2 hours @ 204°C	reverted to liquid	50

Tear Strength, psi

I (Thiokol LP)	II (Permapol P-5)
50	160

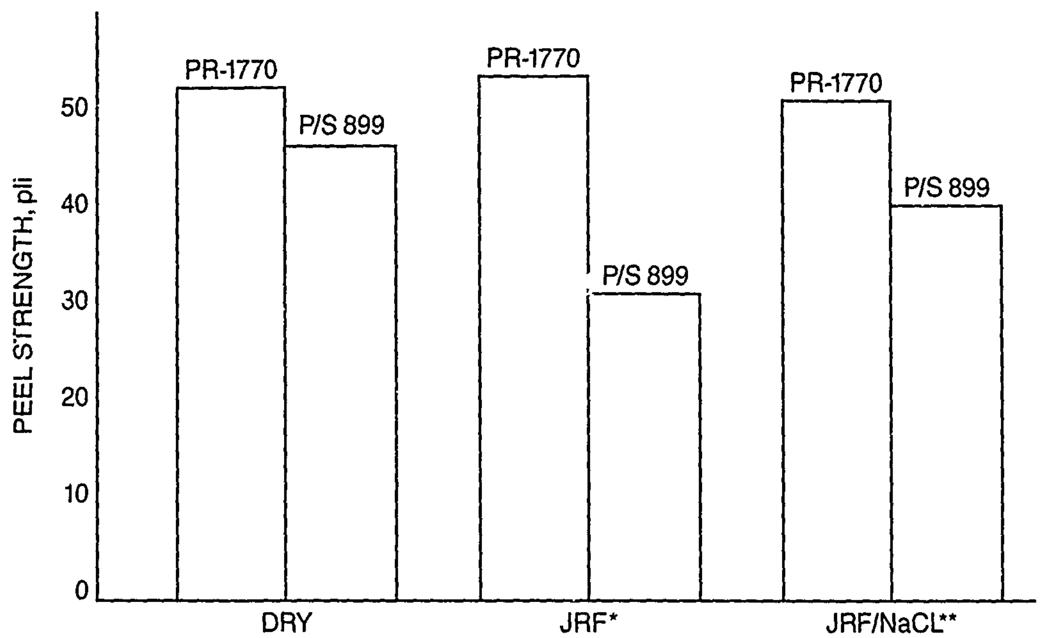
Modulus, MPa

	I (Thiokol LP)	II (Permapol P-5)
100%	150	300
200%	250	580



Peel Strength, pli

	I (Thiokol LP)	II (Permapol P-5)
Dry	45	52
After immersion in JRF (7 days @ 50°C)	30	50



*Immersed in JRF Type VII 7 days @ 140°F.
**Immersed in JRF/NaCl water, 50/50, 7 days @ 140°F.

Fuel Vapor Permeability
Mil-T-27422B

Essentially identical sealant formulations were prepared using (1)Thiokol LP polymers and (2) Permapol P-5 polymer derived from these LP polymers by chemical modification with DMDS. In order to obtain viscosity and molecular weight in the same range as Permapol P-5 polymers, a blend of Thiokol LP-2, LP-31, and LP-3 polymers was prepared and used as a control.

After mixing 100 parts of each base composition with 10 parts of the accelerator composition, cured specimens of these sealants compositions were prepared in the form of 0.127 centimeter thick sheets. These sheets were cured for 14 days at room temperature. At the end of this period, 7.62 centimeter diameter circular discs were cut from these sheets and bolted on to a flanged aluminum cup containing 10 grams of jet reference fluid (Type 7)[3] These cups were then exposed at 77°F. for 30 days.

TABLE 3

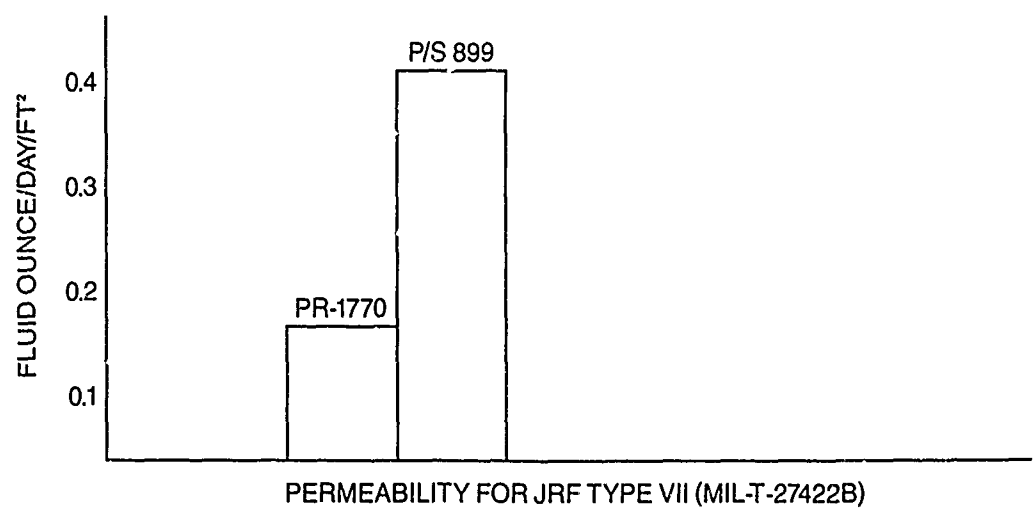
Fuel Vapor Permeability of Sealants

Base Composition	Formulations – Parts by Weight I	II
Thiokol LP Polymer Blend	10C	–
Permapol P-5 (Chemically Modified with Dimercapto Diethyl Sulfide)	–	100
Phenolic Resin	10	10
Titanium Dioxide	4	4
Calcium Carbonate	60	60
Catalyst	1	1
Accelerator Composition		
Manganese Dioxide	60	60
Plasticizer	30	30
Retardant	0.5	0.5
Catalyst	5	5
Accelerator to base ratio is 1:10		
Permeability Results		
Loss in Weight, fluid ounce/day/square foot @ 25°C	0 38	0.15

The fuel vapor permeability was determined by measuring the weight loss of fuel from each cup and was calculated as the loss in fluid ounce per day per square foot.

The sealant compositions and the permeability results are shown in Table 3.

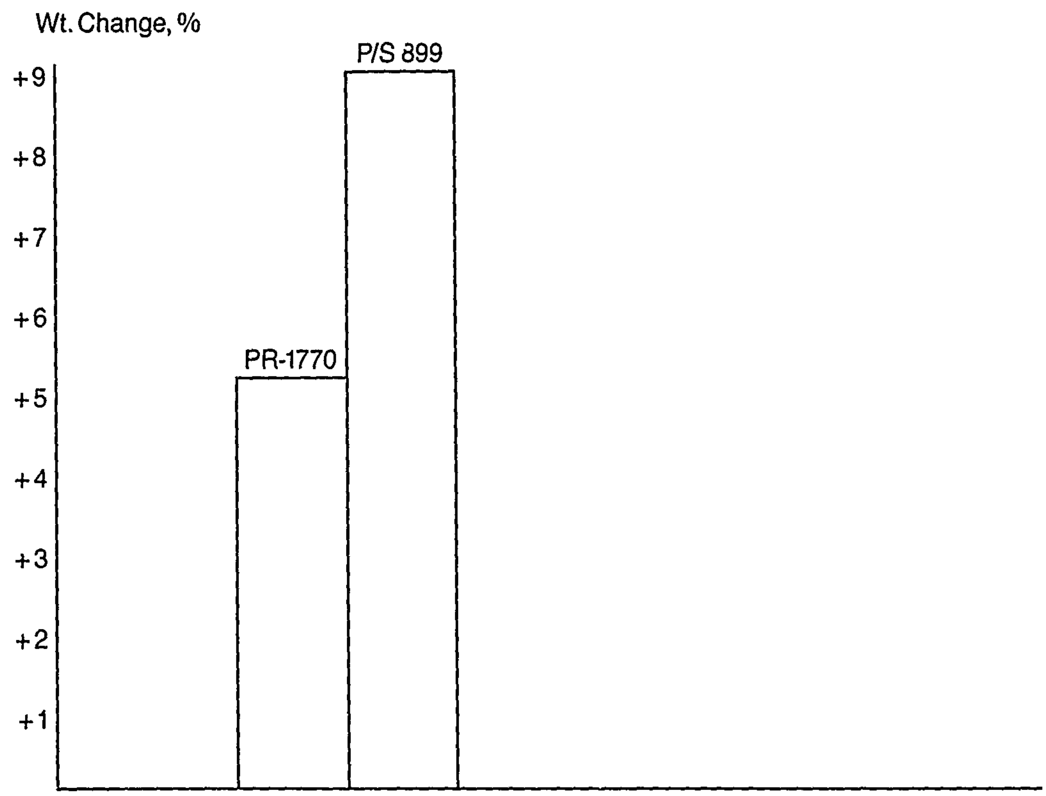
These results clearly demonstrate that sealant based on Permapol P-5 polymers incorporating dimercapto diethyl sulfide as the chemical modifier exhibits much lower fuel vapor permeability.



Weight Change

7 days @ 140°F.
in JRF Type VII

PR-1770B	P/S 899B
+5%	+9%



Jet Reference Fuel Type VII
(Material Immersed for 7 days @ 140)

FUEL RESISTANT COATINGS FOR METAL AND COMPOSITE FUEL TANKS

By

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Abstract

Coating systems based on fuel resistant polythioether polyurethane polymers have been developed. These systems are formulated to provide a secondary seal and thereby protect the interior of composite fuel tanks. In addition to fuel resistance they have excellent physical properties, low specific gravity and prevent fuel leakage even after severe impact damage to the composite tank.

Reduction of mechanical damage, prevention of water penetration into the composite, and prevention of leakage through composite imperfections are other desirable properties of these coatings.

Data are presented showing the fuel resistance and hydrolytic stability of these new materials. The retention of physical properties is tabulated after prolonged environmental exposure to fuel and water.

Impact damage data on coated composites and metal is presented using different energy levels of impact and various thicknesses of coating. The effectiveness of these coatings in sealing composite tanks, both before and after impact damage, is demonstrated.

Fuel and water permeability data are presented. Rapid cure characteristics are also illustrated making these coatings of particular value for production lines.

Coating procedures for sealing disposable or integral fuel tanks without use of faying surface sealants are discussed.

Results on adhesion to metals, composites and conventional aerospace sealants are presented. Ease of repair, surface preparation and product application are also discussed when sealing simple or complex fuel tanks.

The chemistry of polythioether polyurethane polymers is also discussed and compared to conventional polyurethane materials, illustrating how these new coatings provide a new dimension in aircraft sealing technology.

I. INTRODUCTION

In the evolution of the aerospace industry, new demands for lighter, more efficient aircraft have been made. Plastic composites have become very popular and are steadily replacing aircraft metal parts to reduce weight, corrosion and fuel consumption.

The preparation of a high quality composite is a delicate process requiring the expertise of more than one industry. An ideal composite is free from porosity and dry fiber imperfections and has the proper balance of fiber to matrix to obtain optimum physical properties.

The preparation of such composites is very difficult because of variation in raw materials and other parameters influenced by the methods of manufacturing and the complexity of the design.

The possibility of obtaining composite parts with dry fibers and pin hole imperfections is always present, regardless of the stringent manufacturing requirements. These anomalies are detrimental to the performance of a composite fuel tank. Fuel will frequently escape creating dangerous or catastrophic situations.

Another problem associated with composites is their poor impact resistance, especially so, at low temperature. The damage created from impact, even if not visible to the eye, will allow fuel to escape through microcracks.

Because of these limitations, new methods are being sought to seal fuel tanks. There is a need for sealants to be used in conjunction with new designs to lower manufacturing costs, reduce maintenance, and extend life of the airframe. Elastomeric coating materials address all these issues and are now being considered for use as fuel containment membranes

These coatings can be applied in complex cavity configurations to form a fuel tank in spaces where it is difficult to accommodate fuel bladders This will lower maintenance cost and increase fuel capacity.

The same materials can also be used in disposable and auxiliary fuel tanks eliminating the costly faying surface sealing and the possibility of fuel leakage. They have been tested successfully to repair Buna N fuel bladders and are now under consideration for use in bladder construction

2. DEVELOPMENT

Products Research & Chemical Corporation has developed a family of polythioether polymers called Permapol® P-3. These new polymers exhibit excellent fuel resistance and hydrolytic stability over a wide range of temperatures. Permapol P-3 polymers can be tailored to suit specific applications. Mercaptan, hydroxyl and isocyanate terminated P-3 polymers are being manufactured. The isocyanate terminated polymers are used for the preparation of tough coatings designed to protect composite fuel tanks.

PR-2912, based on isocyanate terminated polythioether polymers, is the elastomeric coating discussed in this presentation. This material exhibits excellent physical properties after prolonged exposure to fuel and high humidity environment

Other coatings similar to PR-2912 have also been developed to satisfy applications requiring very high elongations A family of polythioether based coatings is available with elongations ranging from 300% to 800%.

The chemical structure of the backbone unit of Permapol P-3 polythioether polymer is given in Figure 1

Permapol® P-3 Polymer Structure

$$-\!\!\left[(-O-\underset{CH_3}{\underset{|}{CH}}-CH_2-S-CH_2-CH_2-)_{-1}-(O-CH_2-CH_2-S-CH_2-CH_2-)_{-2} \right]\!\!-$$

Fig 1

3. TESTING PROGRAM

3.1 - Equipment

a. **Instron Testing Machine**

b. **Impact Tester Model #172 (ASTM-D2794-74)**

c. **Electronic Scale**

d **Permeability Cup (MIL-T-5578C)**

e. **Aluminum Cylinders to Simulate Fuel Tanks**

f **Nitrogen Pressure Line**

3.2 - Materials

a. Graphite Panels (Hercules AW193-PW/3501-6S)
Autoclave Cured 2 hours 355 ± 10°F (179°C ± 6°C) 100 PSI (689 KPa)
Fiber Volume Range 49.2 to 50.2%
Thickness Range 0.083 to 0.084 inch (2.108mm to 2.134mm)

b. PR-2912 (Permapol P-3 Coating)

c. FT136 (Buna "N" Rubber, Goodyear Aerospace)

d. PR-2910 (Fuel Barrier)

e. PR-2309 (Primer for epoxy/graphite composites)

f. Semco Leak Detection Powder 491

g. TT-S-735 Type VII Fuel

h. TT-S-735 Type III Fuel

i. Aluminum Panels [Alloy 7075 Treated Per MIL-C-5541 6 in. x 6 in. (15.2cm x 15.2cm) x 0.040 in. (0.1cm) Thick]

3.3 - Test Conditions

All testing performed at 77° F (25° C) and 50% RH except as noted.

3.4 - Permeability of Composite Panels Before and After Impact Damage

This test has been performed to demonstrate the beneficial contribution made to a composite fuel tank when protected with a specially formulated elastomeric coating. The protection was found necessary in case of impact damage to the composite and when porosity or dry fibers were present as imperfections.

A laboratory set-up was designed to test the permeability of coated and uncoated panels before and after impact damage. The test equipment consisted of a cylinder opened on one end to accommodate the panels to be tested. The opposite side of the cylinder was equipped with a valve and an opening used to fill the jig with fuel (see Figure 2).

A pressure regulator was installed to maintain a constant pressure of 5 PSI (0.35 Kg/cm^2) inside the test jig. Test specimens were machined to be 6 in. x 6 in. (15.2 cm x 15.2 cm) and were impacted at one, two, four, eight and twelve ft.-pounds.

The impact test was performed on uncoated panels and panels coated with various thicknesses of PR-2912 (see Figure 3). A minimum of three panels were impacted for each condition and then mounted in the jigs as seen in Figure 4 and Figure 5.

One thousand grams of JRF fuel (TT-S-735 Type VII) was loaded into each jig through the openings which were then plugged. The jigs were pressurized with nitrogen to 5 PSI (0.35 Kg/cm^2) and fuel leak detector powder was sprayed on the impacted area and around the gasket. This was applied as a visual aid to monitor leaks through the damaged area and to insure the performance of the gasket.

The initial weight of each jig was recorded to the nearest 0.1 gram. The jigs were connected to the nitrogen line and pressure maintained at 5 PSI (0.35 Kg/cm^2) throughout the entire test period by the use of a regulator.

The jigs were reweighed every three days while pressurized. Attention was paid to close the jig valve before disconnecting the set-up from the nitrogen line.

The duration of the test was four weeks with a constant weight loss obtained during the first week. The test duration for the highly damaged panels ranged from a few seconds to a few days.

Table 1 compares the permeability of the epoxy/graphite panels at different levels of impact damage. Table 1A compares the visual damage of these panels after impact.

3.5 - Permeability Test of Aluminum Structures Without the Use of Faying Surface Sealant.

Conventional sealing of a metal fuel tank always involves some type of faying surface sealant. The faying surface sealing is the most delicate step in sealing a fuel tank. There is always the possibility of having some fuel leaks even after a very careful application. These leaks need to be identified and repaired before the fuel tank is approved.

The same problem exists in the fabrications of auxiliary and disposable fuel tanks. This process is a very costly one and is presently being reviewed for economical and technical reasons.

The development of polythioether based elastomeric coatings has created opportunities in sealing technology Products have been developed based on this new polymer technology which are now under intensive evaluation as an alternative to the costly faying surface sealing. This does not imply that the advent of polythioether based coatings has obsoleted a very well established sealing technology Rather, it represents an entirely new range of materials which can either replace or complement existing sealing techniques.

We are presently testing these new coatings in auxiliary fuel tanks where no faying surface has been used. Testing is underway where the coatings are evaluated for both internal and external applications. The application of elastomeric coatings outside the fuel tank is the easiest and most economical way to seal an auxiliary tank, while the application of the coating inside the tank is more time consuming because of the various ribs to be coated. In either case the application is much easier and more economical than using a faying surface sealant. The tanks sealed in this manner are undergoing long term testing after passing the initial pressurization test.

Testing has been done in the laboratory to simulate the permeability of a metal fuel tank without faying surface sealing. The test procedure of paragraph 3.4 was used. Experimental panels were prepared as seen in Figure 6. Excellent performance was obtained as indicated in Table 2.

Aluminum panels were also tested with and without coatings after impact damage. The protection given by the coating is again demonstrated (see Table 3 and 3A).

4. MATERIAL CHARACTERISTICS

4.1 - Physical Properties

Permapol P-3 based coatings are low viscosity materials capable of application by conventional spraying equipment, roller or brush. They will cure at 77°F (25°C) to give tough coatings with excellent physical properties over a wide range of temperatures [from -65°F (-54°C) to 350°F (177°C)]. They have outstanding fuel resistance, are hydrolytically stable and retain flexibility at low temperatures.

These materials have been exposed to jet reference fuel (JRF) at 140°F (60°C) and to 100% RH at 158°F (70°C) for over one year with no appreciable change in tensile strength and elongation. After this exposure the tensile strength and elongation were approximately 30-35% less in saturated conditions, but in a dry state the tensile strength and elongation values returned to the original (see Table 4, Table 5, Graph 1, Table 6, Graph 2). The polyester urethane used as a control was completely degraded by hydrolysis after this exposure (see Graph 3).

4.2 - Heat Resistance

Tensile properties of PR-2912 have been investigated after exposure at various temperatures. Good retention of physical properties was obtained as seen in Table 7.

Thermal rupture was also tested to evaluate sealing performance after exposure to jet reference fuel (JRF). The test was conducted in accordance to MIL-S-8802 with the exception of using 0.020 inch (0.5 mm) thick coating in place of 0.125 inch (3.18 mm). Results are shown in Table 8

4.3 - Tear Strength

The tear strength of PR-2912 was tested in accordance with Test Method ASTM-D-624 Die C Values were determined before and after immersion in jet reference fuel and in 3% aqueous salt solution (see Table 9).

4.4 - Permeability

The permeability of PR-2912 in fuel and water has been determined and compared to Buna "N" rubber. Results to date indicate that Permapol P-3 materials have permeability that is equivalent or better than that found in Buna 'N" rubber used in fuel bladders. Comparison test data are provided in Table 10.

4.5 - Adhesion

Primer must be used to obtain good adhesion of PR-2912 to substrates. The primer will allow the coating to retain adhesion after exposure to fuel and water. Table 11 shows a variety of primers suggested for different substrates.

4.6 - Repairability

Permapol P-3 coatings can be easily repaired should the need arise. The same product can be freshly mixed and applied to the old cured coating. Conventional sealants like PR-1422 B-2 or

PR-1750 B-2 can also be used as a repair material. It is important to abrade the coating if older than 8 hours to obtain adhesion (see Table 12).

5. SUMMARY

Highlighted in this paper is an elastomeric coating based on a new polythioether polymer technology. Due to the nature of the structure, these liquid polymers have inherent resistance to fuel, water, high temperature, and retain flexibility at temperatures as low as -65° F (-54° C).

A variety of Permapol P-3 based coatings are under long term testing as protective coatings for composite fuel tanks to seal porosity and to contain fuel in case of impact damage.

Other applications of these coatings are in metal fuel tanks to replace the faying surface sealant and in the integral tanks as an added sealing protection besides the conventional sealing.

The high elongation Permapol P-3 based coating (PR-2911) has been approved by the department of the U.S. Navy for the repair of Buna N fuel bags.

This material is also under consideration for the fabrication of fuel bags because of its excellent flexibility and fuel and water resistance all of which are essential to the performance of a fuel bladder.

6. BIOGRAPHY

Santo Randazzo is a graduate of the University of Siracusa, Italy, with a degree in Industrial Chemistry. Following ten years with Ferro Corporation where he was responsible for the development of high performance prepregs for graphite and Kevlar composites, he joined Products Research & Chemical Corporation in 1977.

In his capacity as Product Manager, he is involved in the development of coatings, adhesives, and syntactics for the aerospace industry. His most recent work includes the development of the Permapol P-3 polythioether based coatings for aerospace applications. He has been a member of SAMPE since 1968.

7. REFERENCES

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8. ACKNOWLEDGEMENT

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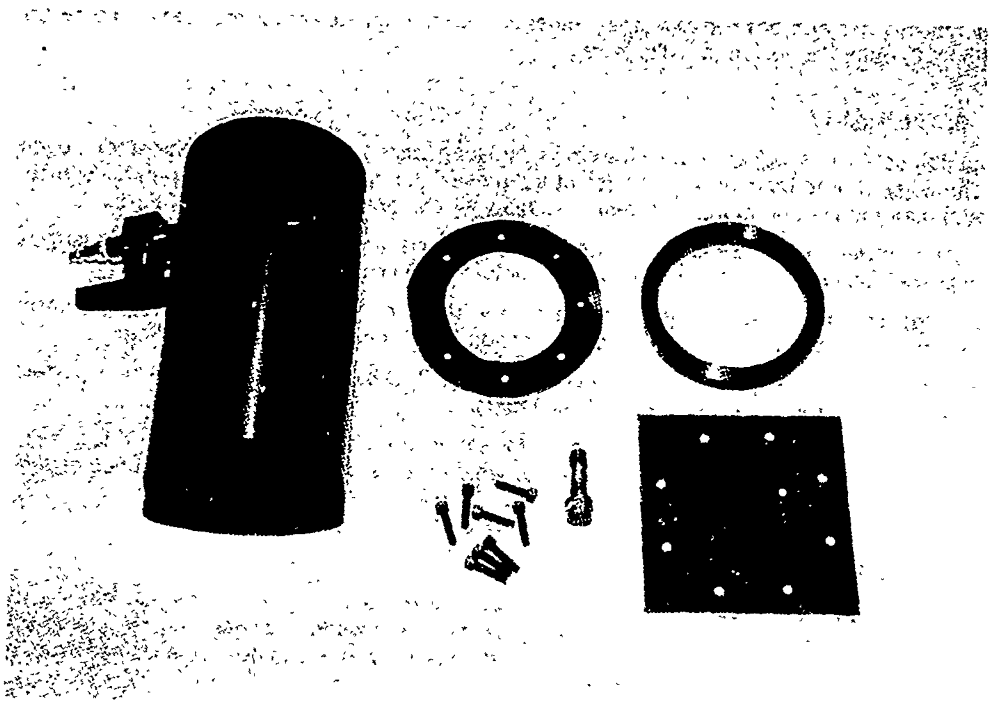


Fig. 2

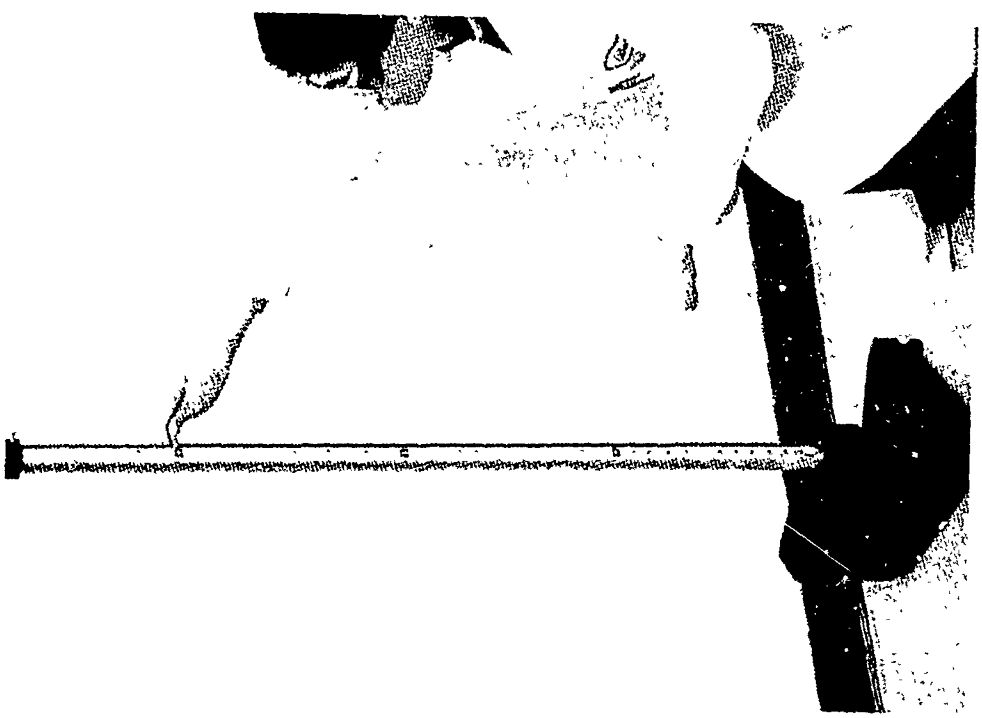


Fig. 3 (ASTM D2794 0.635 Indentor)

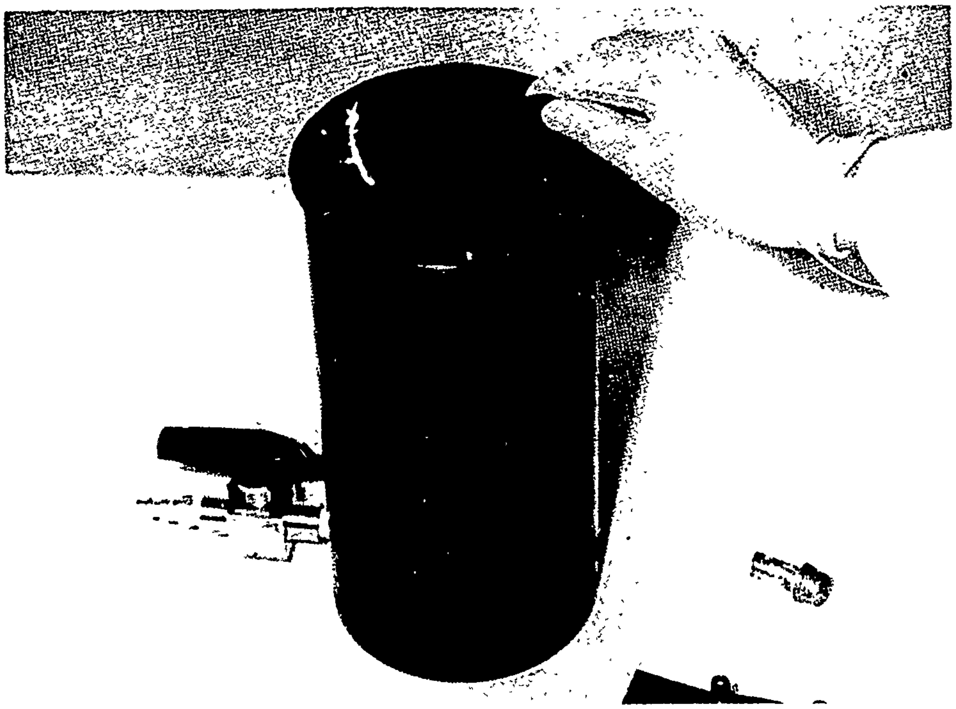


Fig. 4-1

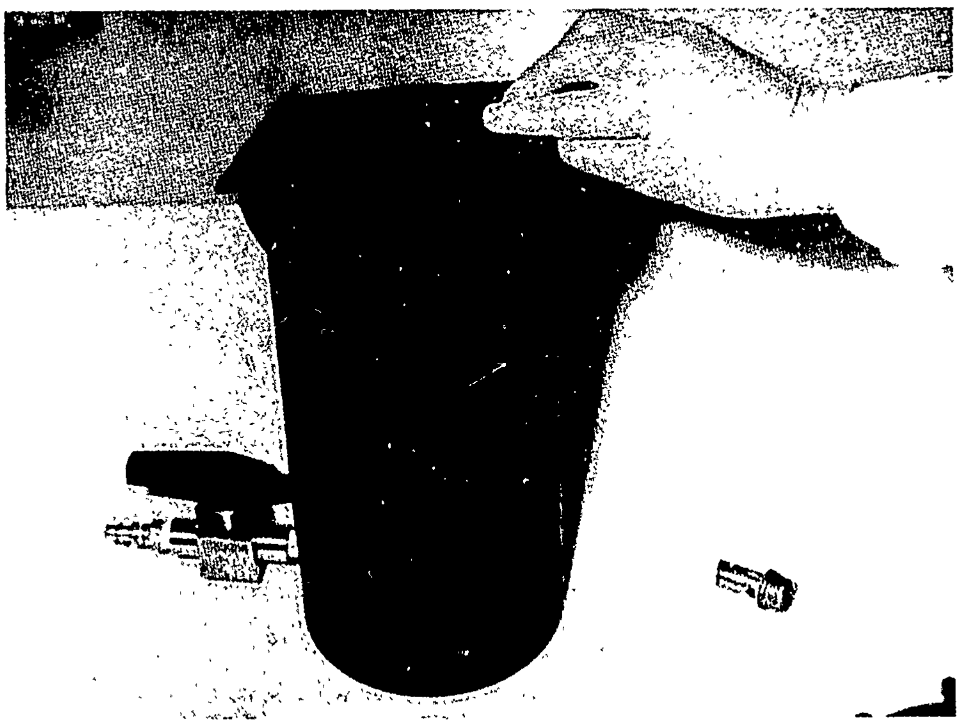


Fig. 4-2

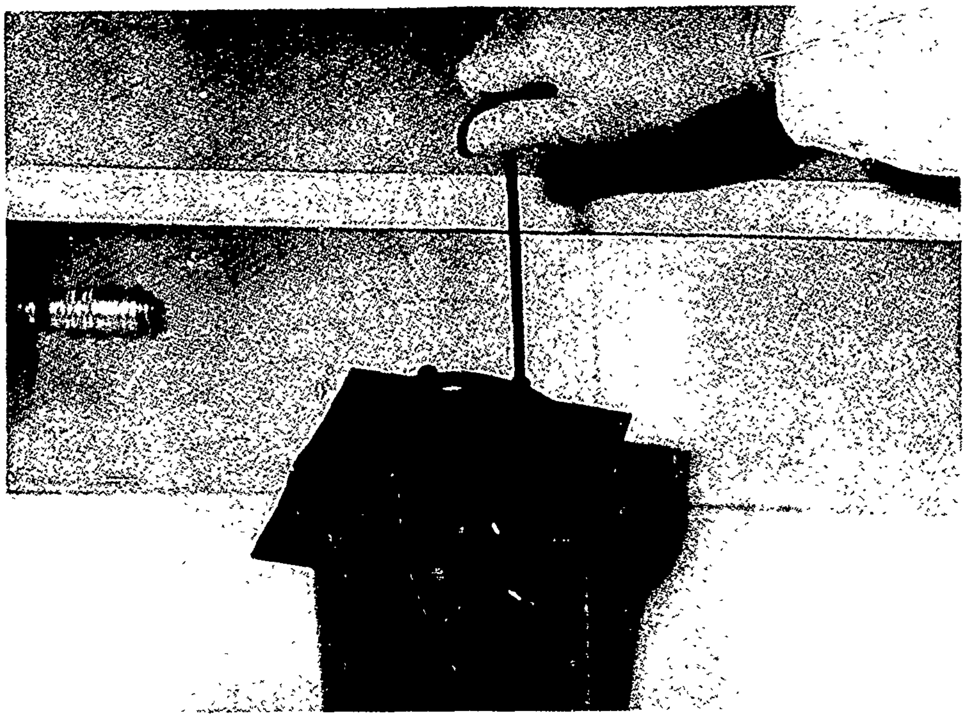


Fig. 4-3

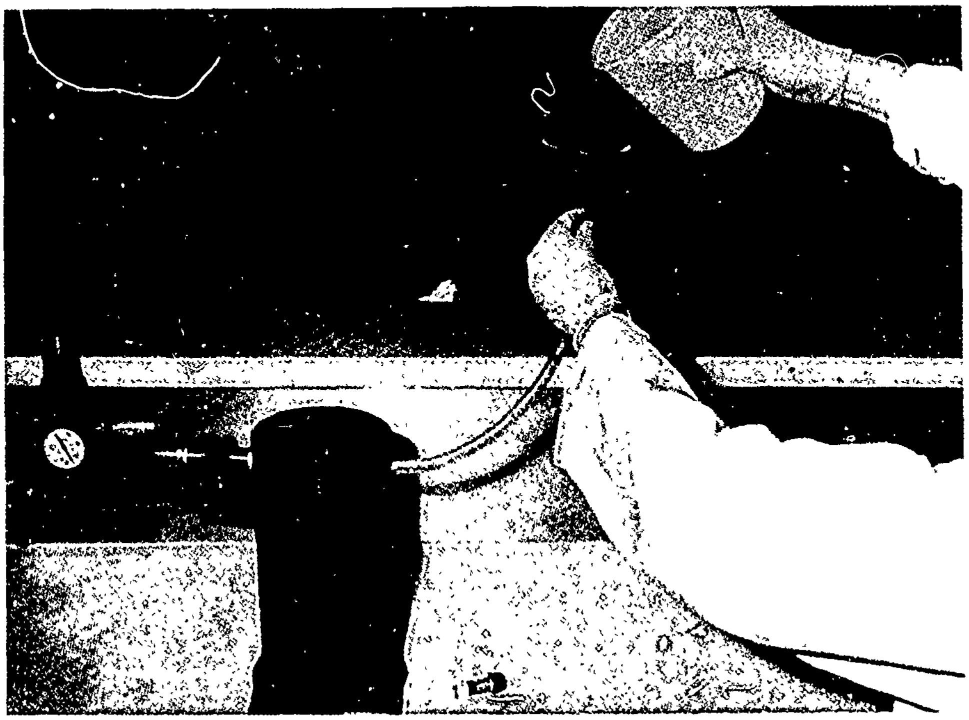


Fig. 4-4

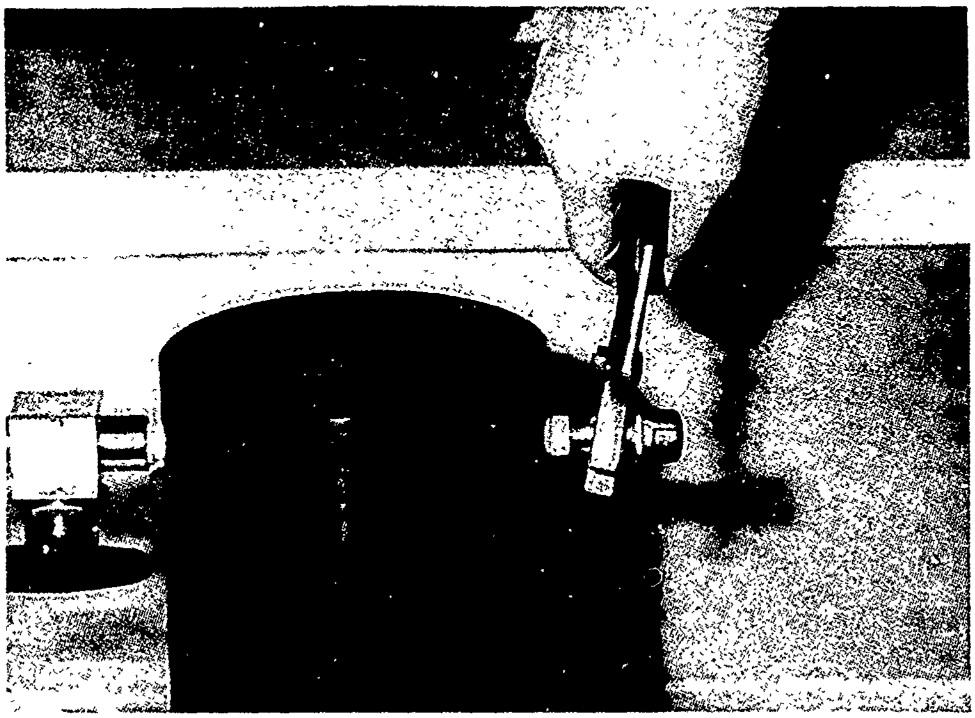


Fig. 4-5

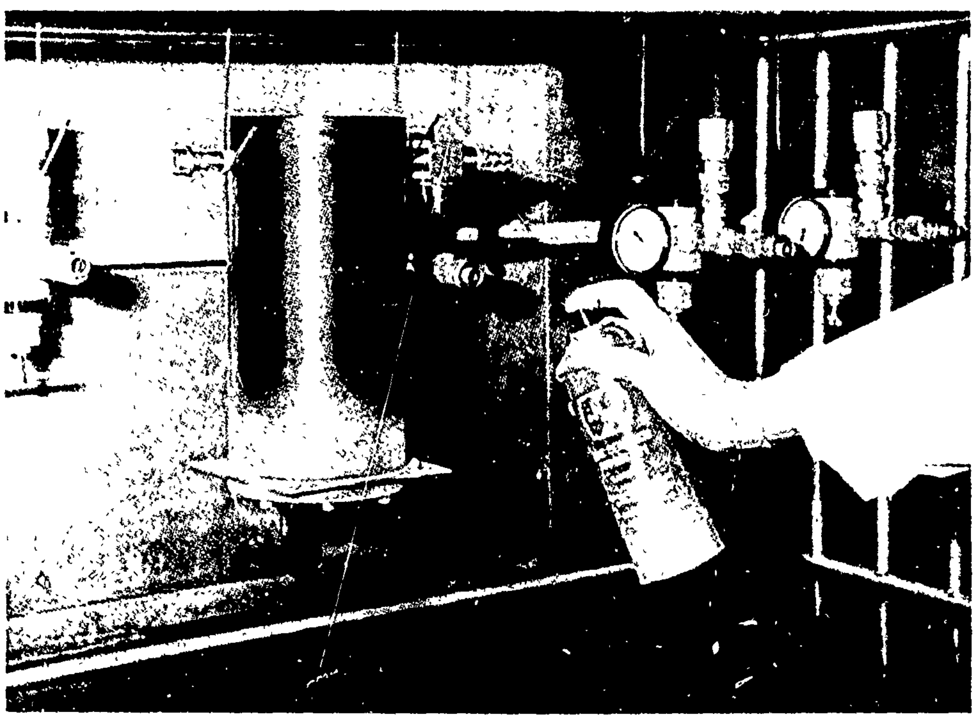


Fig. 4-6

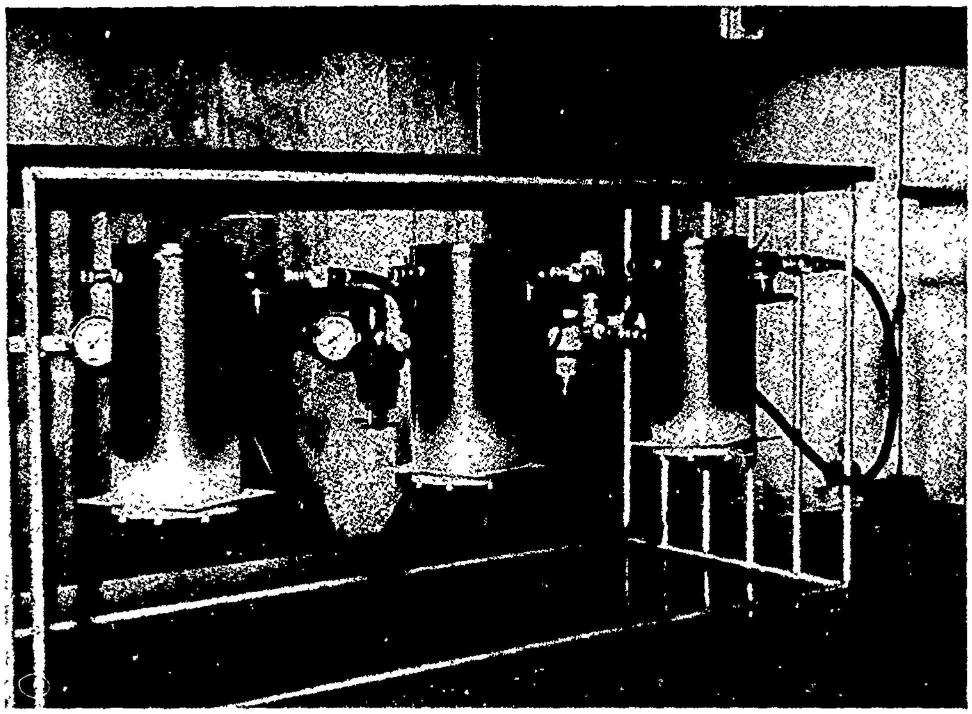


Fig. 5

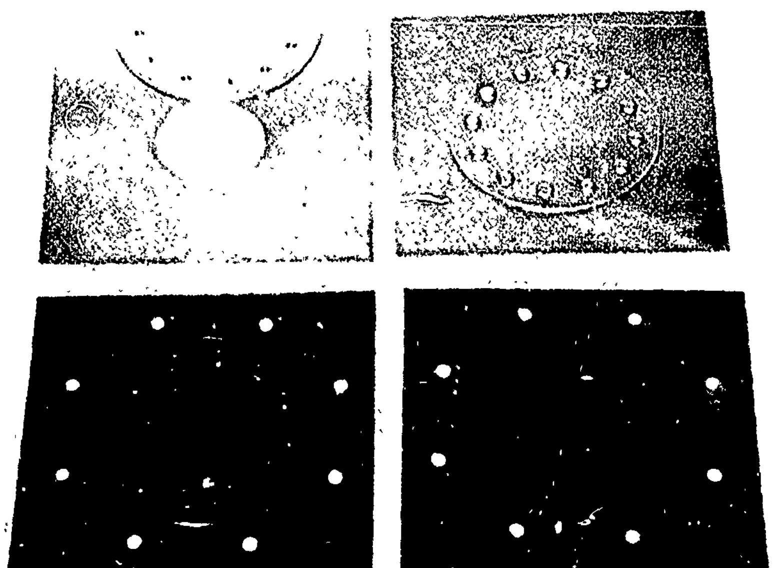
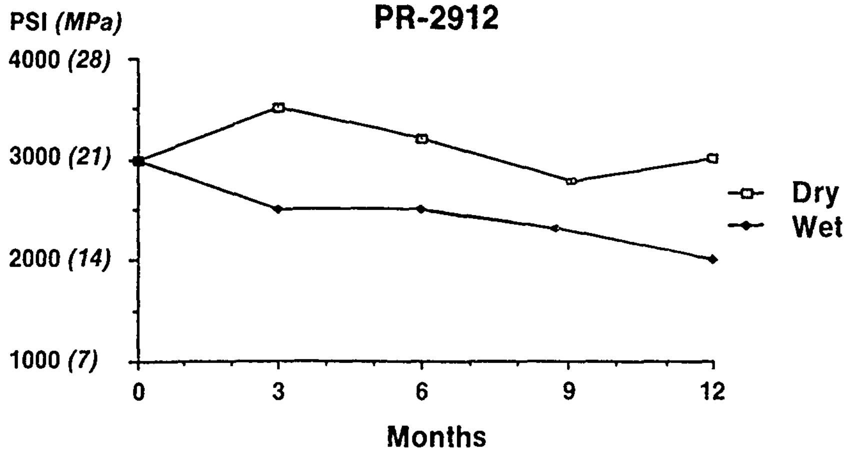


Fig. 6

Graph 1
Exposure in JRF at 140° F *(60° C)*
Tensile Strength at 77° F *(25° C)*

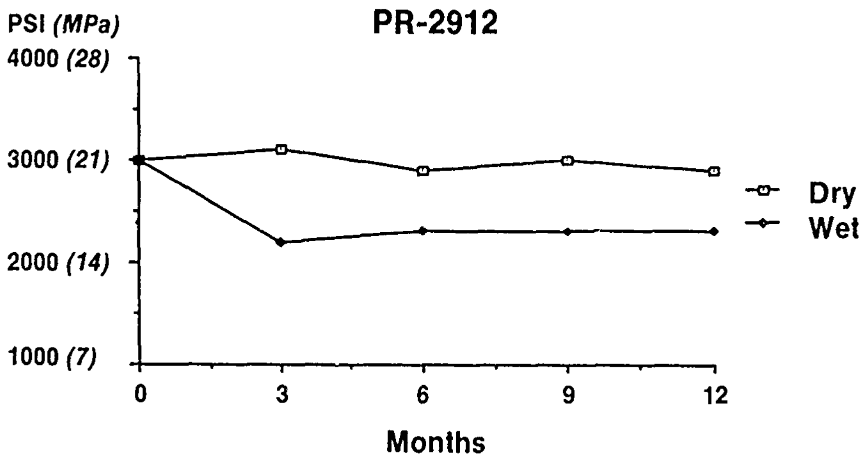


% of Tensile Retained

Wet	83	83	77	67
Dry	117	107	93	100

Wet = Tested just after removal from fuel chamber
Dry = Tested after allowing the wet specimens to dry 24 hours at 140° F *(60° C)*

Graph 2
Exposure in 100% R.H. at 158° F *(70° C)*
Tensile Strength at 77° F *(25° C)*



% of Tensile Retained

Wet	73	77	77	77
Dry	103	97	100	97

Wet = Tested just after removal from fuel chamber
Dry = Tested after allowing the wet specimens to dry 24 hours at 140° F *(60° C)*

Graph 3
Effect of Heat and Humidity Aging on Tensile Strength for Permapol® P-3 Urethane and Conventional Polyester Urethane

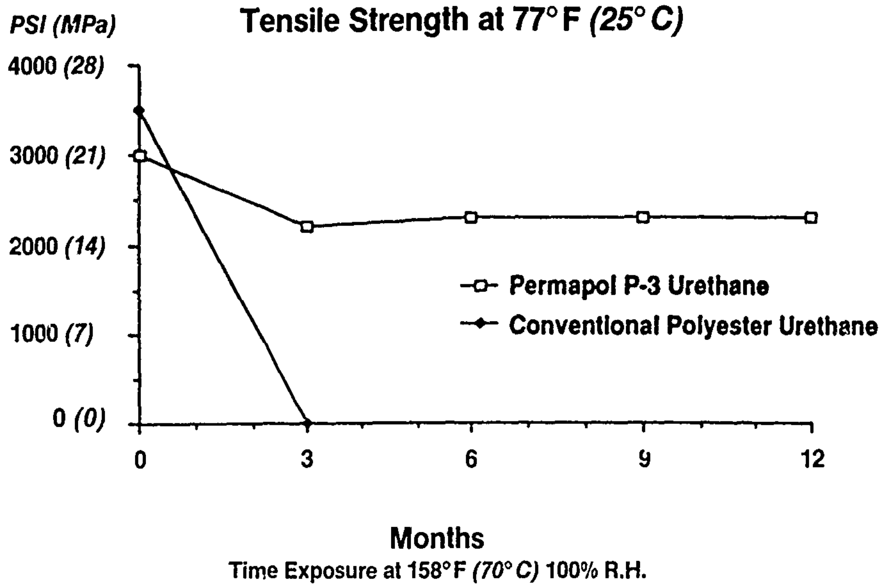


Table 1
Fuel Permeability of Epoxy/Graphite Composites Before and After Impact Damage

Impact Foot-lbs. *(J)*		Uncoated Panels Wt. Loss (gms/day)	PR-2912 Coated Panels 0.005 0.13	0.015 0.38	0.035 in. 0.89 mm
			Wt. Loss (gms/day)		
0	*(0)*	0	0	0	0
1.0	*(1.4)*	0.07	0	0	0
2.0	*(2.7)*	11	0.03	0	0
4.0	*(5.4)*	53	0.08	0.04	0.01
8.0	*(10.8)*	31 kgs			0.12
12.0	*(16.3)*	6336 kgs			0.13

Test conditions: Tested per paragraph 3.4
Composite panels: Hercules AW 193-PW/3501-6S as described in paragraph 3.2

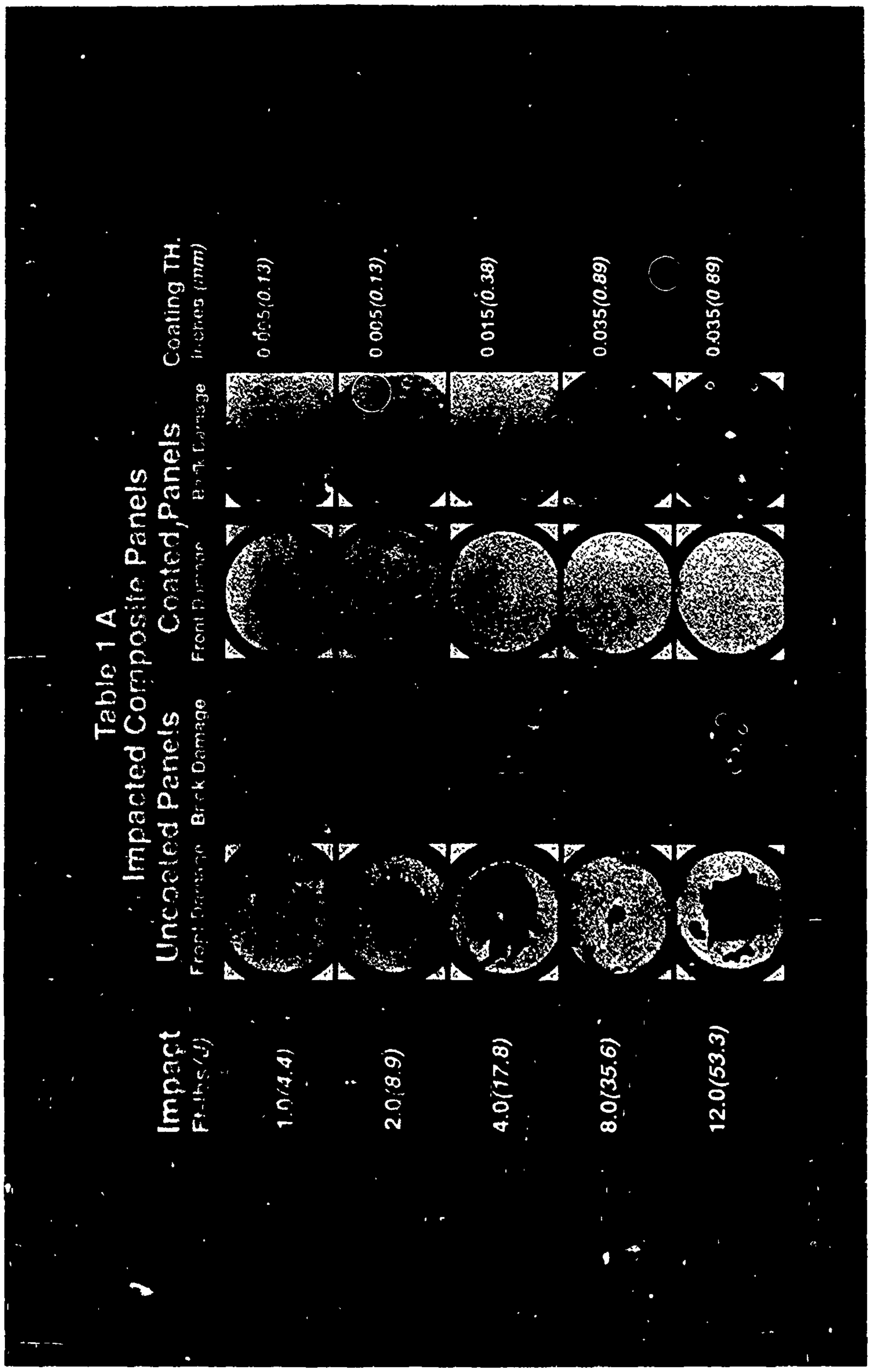


Table 1 A
Impacted Composite Panels
Impact
Ft-lbs (J)
Uncoated Panels
Front Damage
Back Damage
Coated Panels
Front Damage
Back Damage
Coating TH.
Inches (mm)
1.0(4.4)
0.005(0.13)
2.0(8.9)
0.005(0.13)
4.0(17.8)
0.015(0.38)
8.0(35.6)
0.035(0.89)
12.0(53.3)
0.035(0.89)

Table 2
Fuel Permeability of PR-2912 Coating as a Replacement for Faying Surface Sealing

Application	External	Internal
Coating Th. in. *(mm)*	0.020 *(0.5)*	0.020 *(0.5)*
Wt. Loss *(Gms/m/Day)*	0.2	0.2
Wt. Loss *(Gms/m/Day)* Using PR-2910 Barrier	- 0.01	- 0.01

Test Conditions: Tested per paragraph 3.5
Aluminum Panels: Alloy 7075 treated per MIL-S-5541 0.04. in. *(1.02mm)*. Fig. 6.

Table 3
Fuel Permeability of Aluminum Panels After Impact Damage

Impact Foot-lbs. *(J)*	Uncoated Panels Wt. Loss (gms/day)	PR-2912 Coated Panels 0.010 0.25	PR-2912 Coated Panels 0.018 0.38	PR-2912 Coated Panels 0.045 in. 0.89 mm
		Wt. Loss (gms/day)		
4.0 *(5.4)*	0	0	0	0
8.0 *(10.8)*	144	0.09	0.02	0
12.0 *(16.3)*	6100 kgs			0.03

Test conditions: Tested per paragraph 3.4
Aluminum Panels: Alloy 7075 treated per MIL-S-5541 0.040 in. (1.02mm)

Table 3 A ( )
Impacted Aluminum Panels

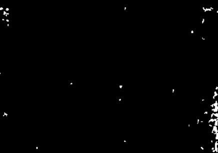
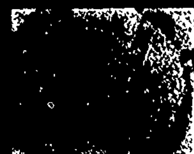
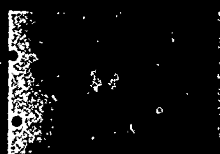
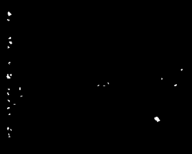
Impact Ft-lbs*(J)*	Uncoated Panels Front Damage	Uncoated Panels Back Damage	Coated Panels Front Damage	Coated Panels Back Damage	Coating TH Inches *(mm)*
4.0*(17.8)*					
8.0*(35.6)*					0.010*(0.25)*
12.0*(53.3)*					0.035*(0.89)*

Table 4
Material Properties
PR-2912

Hardness, Shore D	45
Tensile Strength, PSI *(MPa)*	3000 *(21)*
Elongation %	350
Viscosity poise (Pa.s)	
Part A	100 *(10)*
Part B	1 *(0.1)*
Mixed	25 *(2.5)*
Application Life, Hours	1
Cure Rate: 77° F (25° C) 0.02 in. (0.5 mm) Coating Thickness	
30% of Ultimate Cure (hours)	24
60% of Ultimate Cure (hours)	72
100% of Ultimate Cure (days)	14

Table 5
Exposure in JRF at 140° F *(60° C)*
Permapol® P-3 Coating

Exposure (Months)	Tensile Strength At 77° F *(25° C)*		% Elongation At 77° F *(25° C)*	
	PSI *(MPa)*	PSI *(MPa)*		350
0		3000 *(21)*		
	Wet	Dry	Wet	Dry
3	2500 *(17)*	3500 *(24)*	300	400
6	2500 *(17)*	3200 *(22)*	330	400
9	2300 *(16)*	2800 *(19)*	280	380
12	2000 *(14)*	3000 *(21)*	280	340

Note: Wet = Tested just after removal from humidity chamber.
Dry = Tested after allowing wet specimens to dry for 24 hrs. at 140° F *(60° C)*.

Table 6
Exposure to 100% R.H. at 158° F *(70° C)*
Permapol® P-3 Coating

Exposure (Months)	Tensile Strength At 77° F *(25° C)*		% Elongation at 77° F *(25° C)*	
	PSI *(MPa)*	PSI *(MPa)*		350
0		3000 *(21)*		
	Wet	Dry	Wet	Dry
3	2200 *(15)*	3100 *(21)*	330	350
6	2300 *(16)*	2900 *(20)*	375	340
9	2300 *(16)*	3000 *(21)*	400	360
12	2300 *(16)*	2900 *(20)*	400	350

Note: Wet = Tested just after removal from humidity chamber.
Dry = Tested after allowing wet specimens to dry for 24 hrs. at 140° F *(60° C)*.

Table 7
Heat Resistance of PR-2912

	Initial	After 24 hrs. at 300° F *(149° C)*	After 8 hrs. at 350° F *(177° C)*	After 24 hrs. at 350° F *(177° C)*
Tensile Strength, PSI *(MPa)* & % Elongation at -65° F *(-54° C)*	8000 *(55)* 15			
Tensile Strength, PSI *(MPa) & % Elongation at 77° F (25° C)*	3000 *(21)* 350	2800 *(19)* 330	1600 *(11)* 350	1000 *(7)* 150
Tensile Strength, PSI *(MPa)* at 180° F *(82° C)*	1700 *(12)*			
Tensile Strength, PSI *(MPa)* at 250° F *(124° C)*	*1300 (10)*			
Tensile Strength, PSI *(MPa)* at 300° F *(149° C)*	*800 (6)*			

Table 8
Thermal Rupture
Permapol P-3 Coating (PR-2912)

Thermal Rupture After two Weeks Immersion in JRF at 140° F *(60° C)*
Coating TH = 0.02 in. *(0.5 mm)*

Test Temperature	Thermal Rupture (MIL-S-8802)
180° F *(82° C)*	Passes
250° F *(121° C)*	Passes
300° F *(149° C)*	Passes
350° F *(177° C)*	Passes

Note: Tested per MIL-S-8802 except as noted.

Table 9
Tear Strength (ASTM-D-624 DIE C)
Permapol P-3 Coating (PR-2912)

Tear Strength 77° F *(25° C)*

		Wet	Dry
Initial	lbs/inch *(kgs/cm)*		325 *(58)*
After 2 Weeks Immersion at 140° F *(60° C)* in 3% Salt Water		275 *(49)*	325 *(58)*
After 2 Weeks Immersion at 140° F *(60° C)* in JRF		200 *(36)*	310 *(55)*

Note: Wet = Tested just after removal from humidity chamber.
Dry = Tested after allowing the wet specimens to dry 24 hrs. at 140° F *(60° C)*.

Table 10
Permeability of PR-2912 Versus Buna N
MIL-T-5578C

	Film Thickness Inches *(mm)*	Water Diffusion Rate Fl. oz./Ft²/Day *(cc/m²/Day)*	*Type III Fuel Diffusion Rate Fl. oz./Ft²/Day *(cc/m²/Day)*
PR-2912	0.027 *(0.68)*	0.036 *(11.5)*	0.26 *(82.8)*
	0.014 *(0.36)*	0.074 *(23.6)*	0.55 *(175)*
PR-2912	0.027 *(0.68)*	0.030 *(9.6)*	— 0.01 *(3.2)*
With Barrier	0.014 *(0.36)*	0.07 *(22.3)*	— 0.01 *(3.2)*
Buna N	0.030 *(0.76)*	0.038 *(12.1)*	0.72 *(229)*
Buna N With Barrier	0.030 *(0.76)*	0.022 *(7.0)*	0.02 *(5.7)*

(Goodyear Aerospace FT 136)
* MIL-T-5578C Requirements = 0.025 Fl. oz/Ft²/Day *(8.0cc/m²/Day)* max.

Table 11
Primers for Permapol P-3 Coating (PR-2912)

Primers	Substrates
PR-2909, Primer 1826, MM 425	Aluminum, Titanium
PR-2909	Glass/Epoxy, Graphite/Epoxy, PR-1560MC Coating
Primer 63	Buna N, Polyurethane
Primer 1826	Old and Fresh Aerospace Sealants (PR-1422 B2, PR-1750 B2)

Note: Material exposed to fuel or water must be allowed to dry before repair.
Heated ventilation can be used to speed up the process.
Surface must be abraded and wiped with MEK before application of primer.

Table 12
Repairability
Permapol® P-3 Coatings

	PR-2912
Before Fuel or Water Exposure	Excellent
*After Fuel or Water Exposure	Excellent

Note: Repairs are done as follows:

1. Sand surface of material to be repaired
2. Wipe surface with Methyl Ethyl Ketone
3. Apply freshly mixed compound and allow to cure as indicated in the technical bulletin (sealants such as PR-1422B2 or PR-1750B2 can also be used to repair the coating).

*Material exposed to fuel or water must be allowed to dry before repair.
Heated ventilation can be used to speed up the process.

SPRAY SEALING - A BREAKTHROUGH IN INTEGRAL FUEL TANK SEALING TECHNOLOGY

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SUMMARY

In a continuing effort to increase readiness, a new approach to sealing integral fuel tanks is being developed. The technique seals potential leak sources by spraying elastomeric materials inside the tank cavity. Laboratory evaluations project an increase in aircraft supportability and reliability, an improved maintainability, decreasing acquisition and life cycle costs. Increased usable fuel volume and lower weight than conventional bladders improve performance.

Concept feasibility has been demonstrated on sub-scale aircraft fuel tanks. Materials were selected by testing sprayable elastomers in a fuel tank environment. Chemical stability, mechanical properties, and dynamic durability of the elastomer are being evaluated at the laboratory level and in sub-scale and full scale aircraft component fatigue tests.

The self sealing capability of sprayable materials is also under development. Ballistic tests show an improved aircraft survivability, due in part to the elastomer's mechanical properties and its ability to damp vibrations. New application equipment, and system removal and repair methods are being investigated.

INTRODUCTION

With availability of the internal volume more restricted in each new generation of aircraft there is a need to carry internal fuel more efficiently. Military aircraft in service today use removable, rubberized bladders or integral tanks or some combination of the two (Figure 1). Leakage occurs in both current systems and fuel seeps from the cavity drain of a bladder tank or from the structure surrounding an integral tank. This safety hazard directly affects the operational readiness of the fleet.

Bladders are the most widely used containment system. Bladders are made of rubber or fuel resistant elastomers reinforced with fabric. They are generally hand fabricated on a male mold which is destroyed at the completion of the manufacturing process in order to remove it from the bladder. The process is expensive, requires loose tolerances, and produces heavy assemblies. The bladders are complex enough to be damage prone and yet not complex enough to efficiently use available cavity volume.

In a modern and complex fighter/attack aircraft structure the traditional bladder is becoming too complex. Instead an integral tank fuel containment system is proposed by MCAIR which also provides a more efficient seal.

The most popular currently used integral tank sealing methods are fillet/fay surface sealing, channel groove sealing, and adhesive bonding used in conjunction with wet installed fasteners, or with fasteners provided with special sealing features. These methods not only insure a more efficient sealing technique maximizing the useable fuel volume, but they are also considerably lighter.

However, experience with integral fuel tanks has been less than satisfactory. Leaks develop due to the structural deflections, vibrations, extreme temperature variations experienced by high performance aircraft, wear and tear of years of service, tank surface corrosion, and decreasing sealant surface adhesion.

The most popular sealing materials currently in use are polysulfides for fay surface and fillet sealing, non-curing fluoropolymers for groove sealing, and AF-10 fay surface adhesive. Polysulfides, when applied properly, can be a reliable sealing system. They are, however, susceptible to quality problems such as surface contamination, application voids, and fillet cracks in high structural deflection environments.

The main advantage of channel seals is that they can be repaired from outside the tank. They are most widely used on wing structures. The injection seal system is, however adversely affected by structures fit-up and workmanship. A problem also exists with non-curing materials which are not a permanent seal system in that they tend to displace under load and therefore require ongoing maintenance. The effort is prone to increase with age. Additional difficulty is caused by injection sequencing.

The AF-10 fay surface adhesive has been successfully used on wings of various aircraft. It has a good past performance record, but adds complexity and cost to the manufacturing process.

Our engineering team's goal in addressing fuel tank sealing was to demonstrate a sealing concept capable of overcoming the fabrication and performance difficulties of the existing concepts. A concept, that would increase the reliability, supportability and maintainability of the fuel containment system.

METHOD DEFINITION

Investigation of existing fuel tank sealing methods led to the decision to develop a new approach. The objectives were to decrease fuel system and aircraft weight, increase the usable fuel volume, develop a containment system requiring minimum changes for retroactive implementation and, finally, a system capable of performing in the fuel tank environment while subjected to deflections encountered during aircraft maneuvers.

To provide such a system, a new sprayable approach using fuel resistant elastomeric sealants was developed. These sealants are compatible with typical aircraft structural materials, corrosion protection coatings and paint primers. The sealant is sprayed directly onto the tank's interior surfaces and no tooling is required. It can be applied to selected areas within the tank cavity or to the entire structure, encapsulating the tank with an integral coating. It can be implemented in wing and fuselage tanks of new aircraft or installed retroactively on existing aircraft (Figure 2).

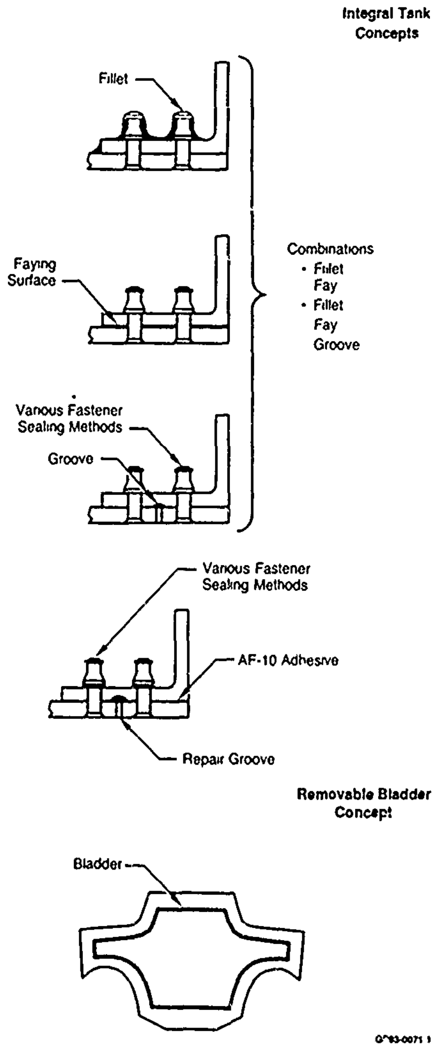

Figure 1. Existing Fuel Tank Sealing Concepts

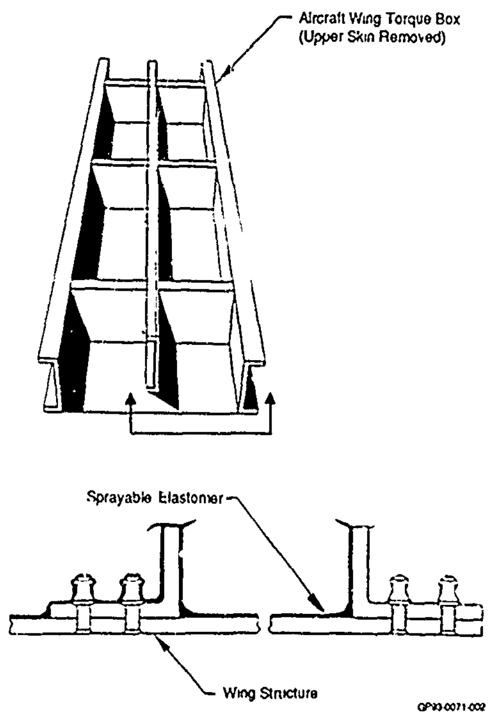

Figure 2. Spray-Sealed Integral Fuel Tank Concept

MATERIAL SELECTION CRITERIA

The prime objective in the initial development of the spray sealing approach was to find a safe and reliable fuel containment material. It was apparent that the search had to be based on requirements known only in a very broad sense, such as fuel resistance, hydrolytic stability, and adequate adhesion and tensile strength in case of fuel containment. It was not possible however, to give numbers to these properties.

Thus, the way to find a satisfactory material was to conduct design element tests, and use results to establish material properties. It became evident that some of the military specification tests used for evaluating sealing materials did not adequately represent the environmental conditions which the materials are exposed to in service. As a result, new methods of testing had to be developed.

The material candidates considered generally had a background of performance in fuel environments. In addition to fuel exposure, several other properties were involved in material selection. These included reversion and temperature resistance, adhesion, physical properties, corrosion resistance, shrinkage, shelf life and application characteristics, and micro-organism resistance. Other properties such as dry time between coats, cure rate, viscosity, etc. were also addressed, but they were considered less important than the others.

Ideally, a sealant should be capable of lasting for at least 20 years without refurbishment, other than localized repair. During that period it is exposed to several severe conditions, and these needed to be assessed.

At the beginning of the program, physical property requirements such as tensile strength, elongation, hardness and tear strength were not well defined. Since then two strength requirements have emerged for sealants. While material with a tensile strength of several hundred kg/cm² (psi) can perform the fuel containment role successfully, several thousand kg/cm² may be required to resist penetration. In both instances however the elongation should be similar, approximately 350-400%.

When the aircraft is on the ground, humidity/temperature conditions within the tank are conducive to reversion of the sealing materials. The environmental situation is recognized in such specifications as MIL-S-8802 and MIL-S-83430 which cover polysulfide materials.

For integral fuel tanks in the current aircraft of interest, the operating temperature range is -54°C (-65°F) to 121°C (250°F) or 149°C (300°F). The upper temperature occurs when the fuel is depleted and thermal soak-back raises the tank temperature. At -54°C the elongation of polysulfide and polyurethane materials and their flexibility are severely affected. At the same time, a thin layer of the seal.. at the edge of a structural joint needs flexibility to elongate with the flexing of the structure. It was later determined that fuel soaked materials can suffer a temporary swelling and softening of the polymer chain at higher temperature.

Adhesion to several types of substrates is also a factor in material selection. Aircraft integral tanks are fabricated from aluminum, titanium, stainless steel, and various types of composites, usually with several types of finishes. Thus, sealants must demonstrate adequate adhesion to all finish systems and structural materials.

Integral fuel tanks contain water sumps and are prone to condensation. They have been recognized as sites for corrosion. Therefore, the sealant must provide corrosion protection. In addition, components of the sealant and any by-products liberated in the cure must be non-corrosive. It is also necessary for the curing mechanism to result in neutral or near-neutral stress in the applied sealant to prevent its separation from the metal surface.

Long application life for the sealant is desired to permit the maximum use of prepared material. However, it usually is not feasible to have both long application life and a short cure which is necessary for reasonable intercoat time. Application lives of 30-45 minutes were found to be acceptable.

Shelf life, while not so critical to an airplane manufacturer, is very important to the services. Repair and retrofit sealants need to have a refrigerated shelf life of 12 months or better.

Finally, material resistance to the saprophytic microorganisms is necessary. Some coatings formerly used in fuel tanks, such as the MIL-S-4383 Buna-N, were identified as nutrients to such organisms. Good housekeeping, fuel biocides, and the use of water coalesces in the fuel system have since kept the microorganisms at bay. It can not be assumed however, that the problem will not arise again.

QUALIFICATION REQUIREMENTS

Existing military specifications for aircraft sealants, though often used for basic definitions, are not entirely applicable to the spray-sealing concept. Thus, a new and more stringent qualification test procedure had to be established. First, we had to determine the properties a material must possess to ensure satisfactory performance within a fuel containment environment. Tests from several sealant specifications were combined to formulate the qualification procedure.

When candidate materials were received, short-term screening tests evaluated the material's basic mechanical properties (tensile strength and elongation) at room temperature and at the temperature extremes for the operational environment. Two accelerated screening methods proved to be particularly successful. They are the Thermal Mechanical Analysis (TMA) and the Steamclave.

Thermal Mechanical Analysis (Figure 3) looks at hot fuel resistance by using a sensitive dilatometer to measure expansion of a material as temperature is increased in increments from -100°C (-140°F) to degradation. Two samples of each material are tested. One is an unexposed reference control specimen and the other is preconditioned by soaking in Jet Reference Fuel (JRF) for seven days at 60°C (140°F) (Figure 4). This screening test precedes the standard 70 day test defined by military specifications.

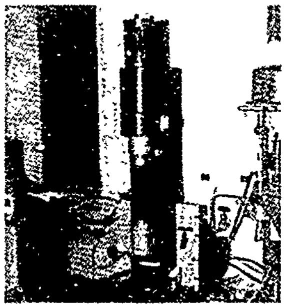

Figure 3. Thermal Mechanical Analysis

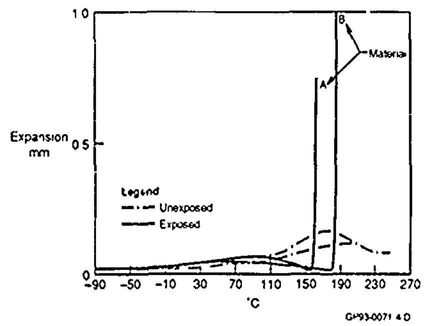

Figure 4. Typical TMA Reading

The paramount property of the sealant is the resistance to degradation by hydrocarbon fuel, in particular JP-4 and JP-5 fuels meeting MIL-T-5624. Thus our long term test efforts to evaluate this property were generally based on the philosophy used for evaluating MIL-S-8802/MIL-S-83430 polysulfide sealant and amounted to 70 days exposure to fuel at 60°C (140°F) (Figure 5). After the exposure, but without drying time, the sealant was tested for tensile strength and adhesion to substrate (peel strength). This procedure typically produced data such as that shown for polythioether urethane in (Figure 6).

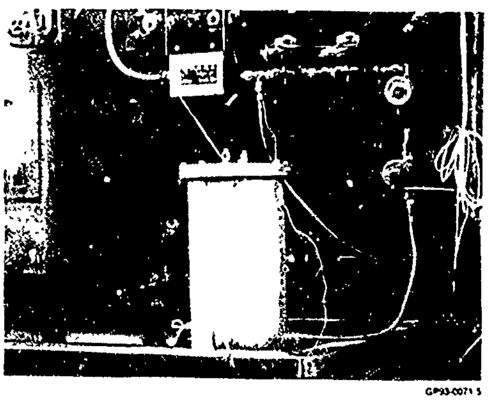

Figure 5. Long Term Fuel Exposure Test

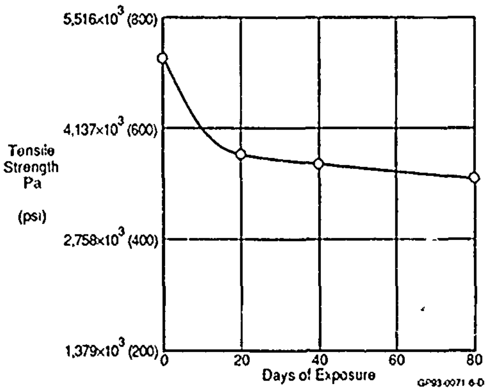

Figure 6. Tensile Strength-Effect of JP-4 Fuel at 60° C (140° F) on Polythioether Urethane

The second accelerated test is hydrolytic stability screening in the steamclave (Figure 7). This is a test in which material samples are placed in a pressure vessel at 103E + 01 Pa (15 psig), 121°C (250°F) and 100% relative humidity (RH). Standard tensile specimens are used and at intervals during the exposure, samples are withdrawn and tested (Figure 8).

Figure 7. Hydrolytic Stability Screening in Steamclave

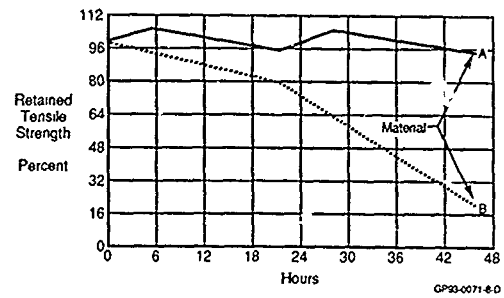

Figure 8. Typical Steamclave Reading

This screening tool, in only a few hours, reveals which materials are unsuitable for a fuel tank sealant application. Forty hours in the steamclave approximates the standard military specification test lasting 120 days. Numerous tests verified the correlation of results with long term exposures (Figure 9).

Hydrolytic stability along with fuel resistance are two of the most important properties for sealing materials. Again the concern is that the sealant endure the presence of humidity and temperature as well as fuel. The acceptance criterion chosen was the retention of 55% of the initial tensile strength after 120 days of exposure to 95% RH at 71°C (160°F). In a few cases, when an elastomer appeared to be especially promising, the test duration was extended to 180, or even 240 days.

Contradicting reversion resistance hydrolytic stability results were obtained, for a prolonged period, in repeated tests of the same materials. It was eventually determined that humidity cabinets do not provide reproducible results (Figure 10). Reversion resistance has also been evaluated by water immersion at 71°C, but no particular advantage was identified. In fact, some investigators opposed the approach because the acid breakdown product of the reversion process serves to catalyze further reversion.

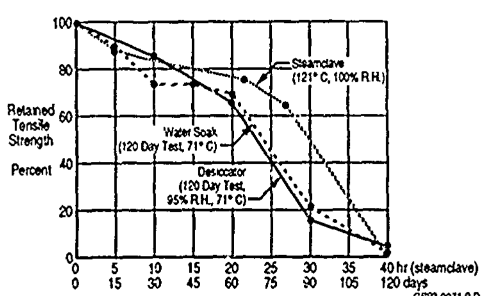

Figure 9. Test Comparison – Tensile Strength of a Polyester Polyurethane in Steamclave vs Long Term Exposure in Desiccator and Water Soak

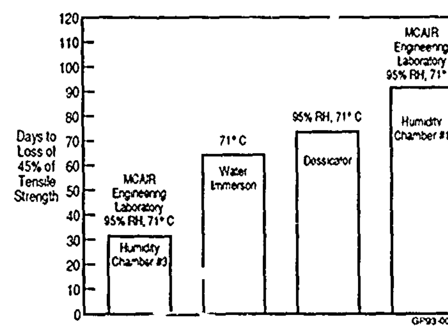

Figure 10. Hydrolytic Stability of a Spray Sealant–Effect of Several Test Methods and Chambers

We found that the most reliable test method is the "desiccator" chamber (Figure 11). The desiccator method uses a mixture of 22% glycerol in water to produce a constant humidity at the constant temperature of 71°C (160°F). The humidity generating medium is located in the lower chamber of the housing while the upper portion provides space for specimens. Numerous verification tests provided most repeatable results (Figure 12).

Another of the major properties addressed is adhesion to materials forming surfaces of the fuel containment compartments. The factors in the adhesion peel strength tests were: (i) the condition of the aircraft, such as new assembly or retrofit, new or contaminated, (ii) the feasibility of the priming (adhesion promoters), (iii) the cleaning procedures to be employed. It was determined that either hot alkaline detergent cleaning with a steam jenny and hot water rinsing, or cleaning with 1.1.1 trichloroethane vapor or hot solvent provided satisfactory surface preparation. In addition to this the polysulfide sealant requires abrasive and solvent cleaning to obtain good adhesion.

Figure 11 Long Term Humidity Exposure Desiccator Test

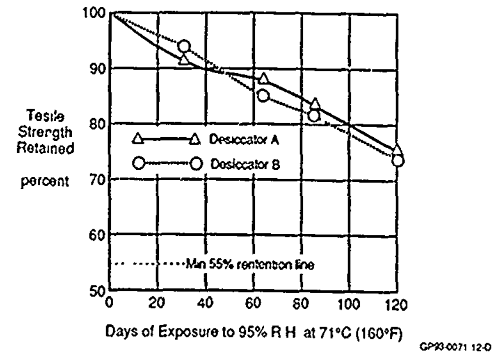

Figure 12. Hydrolytic Stability Testing of a Polythioether Polyurethane Using Desiccator Method.

STRUCTURAL TESTS

Three levels of structural tests are performed following the material screening and verification of mechanical properties, before and after environmental exposure.

The deflection/fatigue beam (Figure 13) is a low cost structural test. The beam deflections represent the response of a selected aircraft fuselage bulkhead to skin attachment to its maximum fuel pressure loading, based on a finite element computer model. The displacement of the skin produced by the internal pressure in a fuel tank is determined at two control points. The bulkhead flange (substructure) is the deflection reference, represented here by metal blocks situated between these points. The blocks are attached to the skin with fasteners representative of typical aircraft joint configurations. Beams are calibrated so that computer determined deflections are obtained at control points. The candidate materials are spray applied on both sides of the structure and cyclically loaded for the representative two aircraft simulated lifetimes. This spectrum includes dry and wet testing in the environmental test facility. Elastomeric coatings are evaluated in peel, shear and extensional loadings.

The environmental test facility (Figure 14) holds fuel at temperatures representative of a variable aircraft thermal spectrum. The fuel temperature is controlled from -53.9°C (-65°F) to 218°C (425°F) by passing steam or liquid nitrogen

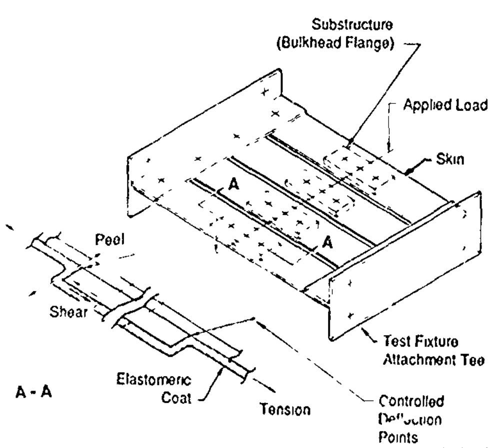

Figure 13. Deflection/Fatigue Beam

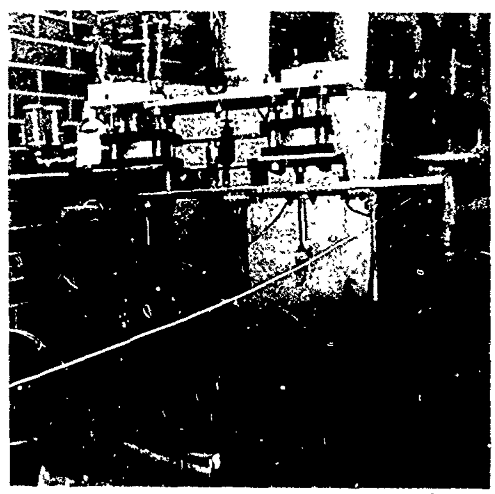

Figure 14. High Temperature Deflection Beam Test Fixture

through heat exchanger coils at the bottom of the tank. The test article is load deflected by pneumatic actuators. To be acceptable, a material is expected to pass the test without cracks, blemishes, sponging, or any other visible deterioration (Figure 15).

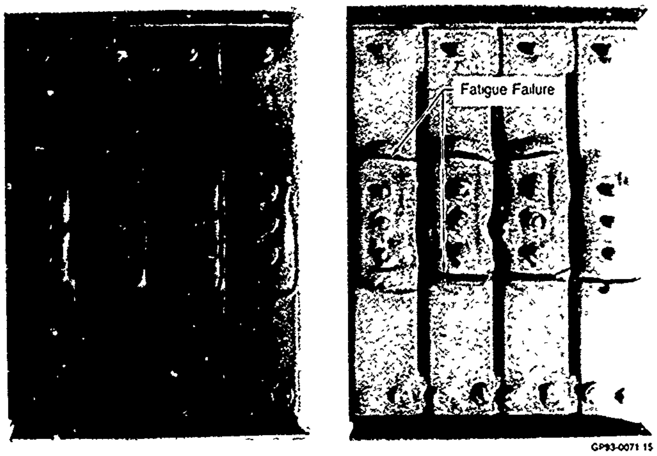

Figure 15. Polythioether Polyurethanes Following Deflection Beam Test

The second level of structural testing takes place with materials applied to wing torque box components. The test facility, test monitoring and support are provided by the Air Force Flight Dynamics Laboratory (AFFDL) at Wright Patterson Air Force Base.

To better demonstrate concept feasibility, boxes are sealed in the areas known from previous tests to be a problem. The lower skin is not part of the test evaluation. It is temporarily left off, while the upper skin and vertical walls of the substructure are spray-sealed with a selected elastomer (Figure 16). No redundant sealing is applied.

After the material is cured, the lower skin is sealed through access in spars by fay and fillet method and attached with interference fit fasteners to the box. Access is then closed and a pressure leak check is performed. Next, the box is mounted on the test fixture (Figure 17).

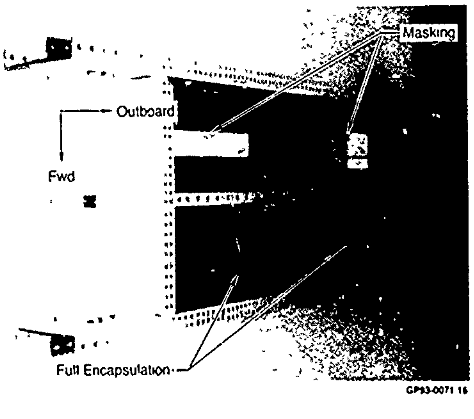

Figure 16. Wing Torque Box Test Component
Air Force Flight Dynamic Laboratory

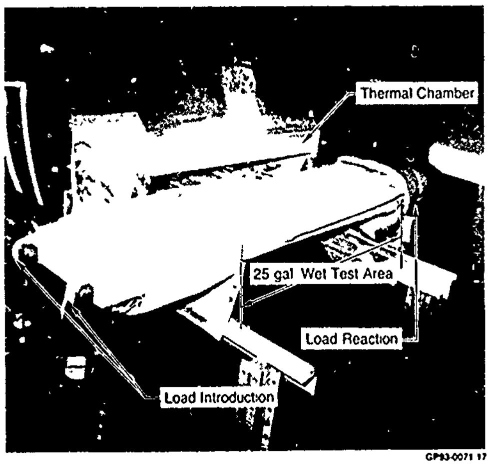

Figure 17. Fatigue and Environmental Test Facility at
Air Force Flight Dynamics Laboratory,

The test is divided into two phases. The first phase includes hydrostatic pressure precycling, strain and deflection surveys, and one simulated aircraft lifetime (8,000 simulated flight hours) of preconditioning including the temperature and positive pressures that take place in the tank while filled or empty.

The second phase represents two lifetimes of a modern fighter aircraft dynamic and environmental spectrum. Wing shear, moment and torsional loads are introduced by two actuators. Loads are reacted by the test fixture with four pinned reactions. Loads applied by the two actuators at the outboard end develop the correct skin stress at the inboard end.

The environmental portion of the test consists of thermal, chemical and positive pressure cycles. The driving factor is the thermal spectrum. The cyclic loads are applied at the appropriate rate to fall within the time spans of each temperature cycle. The combined test environment is contained in a block that is repeated four times during the two lifetime test span.

The test success is measured by the amount of visible outside surface wetness on the upper skin and vertical structure, as defined by the standard safety criteria.

The ultimate test of the spray-sealing system takes place in a generic fuselage fuel tank (Figure 18), which is again conducted by the AFFDL. Designed and manufactured at MCAIR, the tank represents a current technology, high performance, flexible fuselage structure. The sealed tank is tested under repeated loads and an environment of a modern fighter aircraft that includes fuel and pressure spectrum.

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Figure 18. Generic Fuselage Fuel Tank in a Test Fixture at AFFDL, WPAFB

The tank configuration is based on a two-engine fuselage, typical of MCAIR aircraft configurations, the structure has three sections: the load introduction and reaction sections, both dry, and a wet test section. The tank has a homogeneous, continuous structure.

Flight, catapult and arrested landing loads are generated to match actual conditions. Two actuators at the aft end of the fuselage introduce torque and up and down bending. Internal pressure positive (bursting) load cycles are representative of loads encountered during flight, catapult launch and arrested landing. The test also imposes negative (crushing) loads encountered during diving, taxi and defueling operations. Applied loads are reacted by the test fixture at three pinned reactions located at the forward end of the fuselage.

As mentioned earlier, wing boxes are sealed without any redundant systems to demonstrate concept feasibility. In the fuselage, however, the sealing approach follows that of the actual production practices. The walls of the tank that are part of the outside moldline are fay surface sealed and have fasteners installed wet to satisfy corrosion protection requirements.

Leak test instrumentation, hydrostatic pressure test (Figure 19), strain and deflection surveys and preconditioning are similar to those described for wing boxes. However test conditions are significantly more severe.

During the second phase of the test, the fuselage is subjected to a sequence of externally applied loads and internally applied pressures. Each loading point has two external loads and one internal pressure. The task comprises 40 load, internal pressure, and environmental conditions.

The cyclic loads are applied by two load rams. Each is programmed to apply certain percentage of positive or negative loads. The rams are not necessarily at the same level of a given load point. Thus the ram can apply variable rates of shear, bending moment, and torsion.

Test duration is also two lifetimes of an aircraft spectrum. The success criteria of the test are the same as those for the wing.

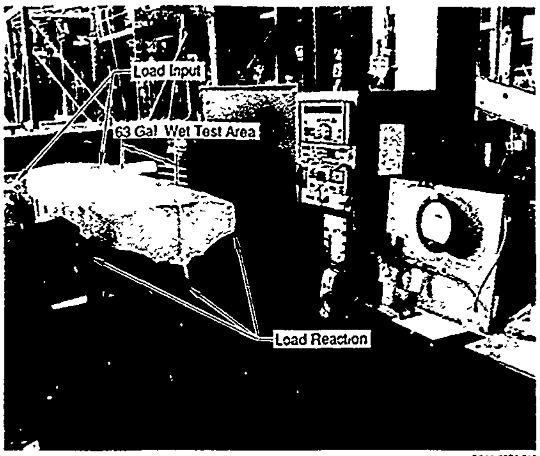

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Figure 19. Generic Integral Fuselage Tank Sealed With Polyurethane, in a 17.3 psi Hydrostatic Pressure Proof Test

BATTLE DAMAGE REDUCTION AND SELF SEALING FOR INTEGRAL TANKS

Another aspect of a fuel tank sealing included in this program is the development of a self-sealing integral tank configuration. Our objective is to obtain a compatible, integral system, sprayable if possible, and effectively competing with the existing technology.

Ordinarily, self-sealing bladder systems consist of a multilayered, fabric-reinforced elastomeric bladder with an embedded layer of natural gum rubber or rubber-impregnated fabric. To prevent premature activation of the self-sealing layer during normal operations, a fuel impermeable barrier is located on the fuel side of the bladder wall. Small amounts of fuel vapors still permeating into the bladder wall are vented through into the space available between the bladder and the tank's structural cavity.

The metal "petals" produced when a projectile passes through the tank wall hold the bladder open, interfering with the self-sealing operation. In current aircraft this has been prevented by placing fiber-reinforced plastic panels to shield the bladder from the sharp petals.

Thus, our effort concentrated on three development tasks: a fuel sensitive, sprayable self sealing system with high swell properties similar to natural gum rubber, a barrier coat to prevent premature activation of the material during normal operation, and an elastomeric layer for the ballistic damage control. The three systems must be compatible and effectively joined together (Figure 20).

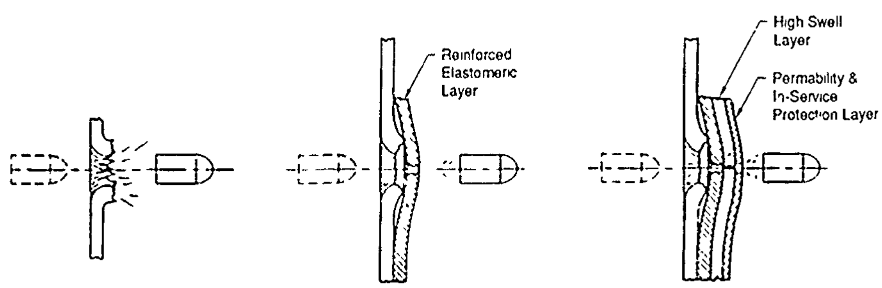

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Figure 20. Self Sealing System for Spray-Sealed Internal Fuel Tanks

A tough sprayable elastomer has been selected to act as a sealant and a ballistic damage reduction system also acting against petalling. Due to the elastomeric nature of the material the entry, and especially the exit wounds, were found to be significantly smaller than the diameter of the projectile. The material stretches during projectile penetration and snaps back afterwards. This shears off a portion of the projecting petals, which are then rejected away from the wound.

Results improve even further when a ballistic cloth is embedded within the elastomeric layer. In a tumbled penetration when the wound increases in size, broken fibers of the cloth stay within the wound, forming a matrix for the high swell sealing system to build upon, while the leak path is restricted to less than the projectile profile.

These tests aim at reducing inlet fuel ingestion after ballistic damage to an integral fuel tank adjacent to the engine inlet. In fact, in hydraulic ram evaluation, the ballistic damage reduction system was found to be as effective as any system tested at controlling inlet fuel ingestion, for the lowest weight penalty and without giving up excessive fuel volume.

The reduced size of the wound can in turn be sealed by a material which reacts chemically by swelling, to a direct fuel exposure. In bladder type fuel tanks this function has been performed by natural gum rubber. The sprayability of gum rubber however, was not regarded as practical and an intensive search had to be conducted for a similar fuel sensitive, high volume swell material with a superior response time, but with sprayable characteristics. Other requirements include resistance to all other fuel tank environments, i.e. temperature, humidity, etc.

Various material concepts in this part of the program were considered. However, the investigative effort was concentrated on sprayable high swell urethanes and isoprenes. Volume swell determinations were conducted in accordance with ASTM D471, except that Jet Reference Fuel No. 2 was substituted for the ASTM fluids. The volume swells and response times for two polyurethanes (P1, P3) and one type of isoprene (I1) are shown in (Figure 21). It is apparent that one of the high swell urethanes (P3) and the isoprene (I1) kept pace with gum rubber (GR) in response time and swell volume.

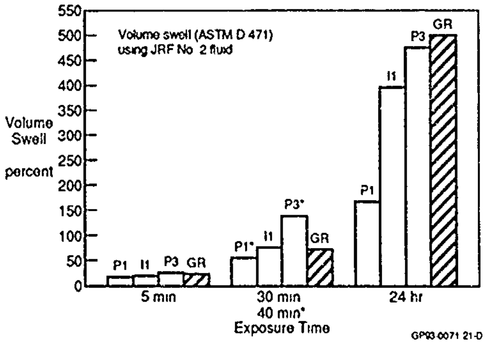

Figure 21. Development of Self-Sealing Materials

Many sealing materials, while they are able to effectively contain fuel, are nevertheless permeable and transmit fuel at a rate sufficient to cause premature activation of encapsulated self-sealing material. A non-permeable film must therefore be placed between the fuel and the self-sealing material. In spray-sealing applications, where elastomers adhere directly to the tank structure, fuel vapors cannot vent across the material. Therefore, a more efficient impervious layer is required. Borrowing from the bladder manufacturers, a nylon terpolymer film is used as a base. Its performance is then compared with that of metallic foil, metallized nylons, and other types of impermeable elastomers. MCAIR is presently conducting a variety of tests aimed at optimizing the system.

APPLICATION TECHNOLOGY

There are on the market a wide range of spray applicators and applications for all solid elastomers, but they are mostly for heavy industry. Sprayed elements are generally large, with simple contour. The thickness and weight of the spray material is secondary. Equipment is crude and bulky. The spraying rate is high and does not allow control of the spraying pattern. Current industrial state-of-the-art in spraying of elastomeric materials does not require a closely controlled coat-by-coat thickness buildup.

Two component solid elastomers also require heat control and a high application pressure. Because of a short pot-life, materials are mixed at the nozzle. Three hoses are required: two for material components and the third one for a line cleaner. No solid elastomer could be identified at this time that would satisfy the dynamic and environmental requirements of aircraft fuel tanks.

Solvent elastomers provide considerably better results than solids. Material mixing takes place at the pump and only two hoses are required. Still, the process often uses airless guns which require high pressures, and the needed thin coat applications are difficult to achieve. Materials become porous and their strength properties become degraded when the overall thickness is beyond control, causing either a weight penalty or inadequate coverage. Applications are therefore limited to uncomplicated, preferably convex shapes.

For solvent elastomers the best spraying to date is obtained with exterior air atomizing. Guns can be operated at low pot and atomizer pressures. For this type of application a special, miniaturized gun was developed, the size of a marker pen. It has a single, coaxial hose in line with its longitudinal axis and a nozzle that allows either straight or angular projection of the spray pattern. It produces an easy, controllable material buildup on the intricate tank structure.

Application of a sealant in a tank is a step-by-step process, following proper surface preparation. Throughout the process, two contrasting colored materials are alternately applied to help identify previously sealed areas. The technique provides a rapid and accurate means of inspecting each sealing step as it is completed. Upon completion, a sprayable integral fuel tank coating is nominally .15 cm thick in the high potential leak areas and .025 cm thick over the remainder of the tank (Figure 22). Thicknesses obtained are verified by means of an eddy current inspection.

A continuous bag-like total encapsulation of the cavity (Figure 23) ensures that there are no leaks due to local sealant disbonds. Alternately, a partial masking away from potential leak sources (Figure 24) is possible where aircraft weight is a critical consideration.

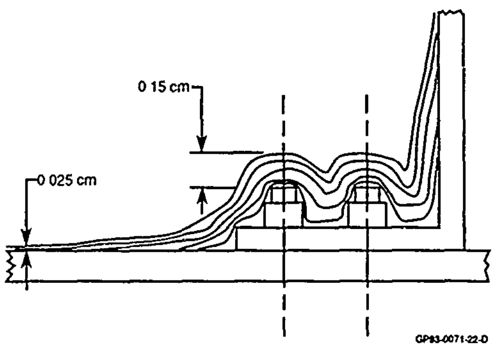

Figure 22. Sprayable Integral Tank Cross Section

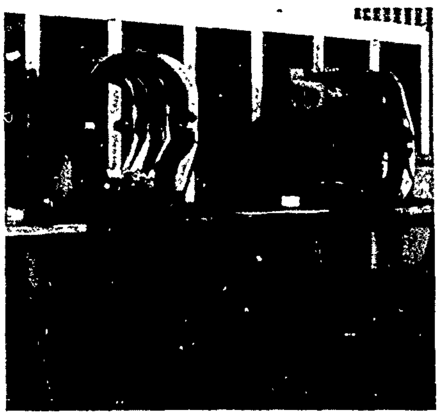

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Figure 23. First Stage Spray-Sealing of F-18 Blue Angel Smoke Generating Oil Tank

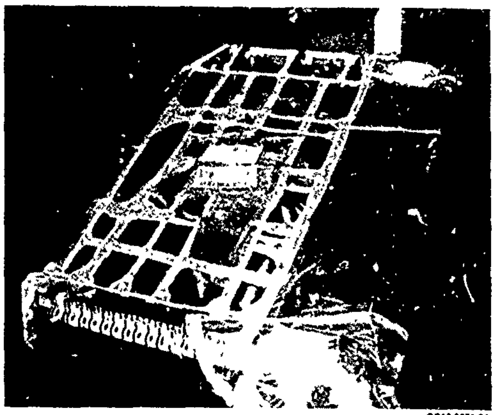

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Figure 24. Partial Spray-Sealing of a Repaired CF-18 Wing

It should be noted that all elastomers vary in viscosity and tend to exhibit changes from batch to batch. They are also sensitive to the environmental conditions under which they are applied. Each new application therefore requires a system calibration and reset.

Effort was also directed towards the repair and removal aspects of a spray-sealed integral tank. It was established that elastomers can be easily repaired by overspraying, troweling, or brushing-on the same material. Most of the polysulfides and polyurethanes can also be patched-up with available stock of the same materials. With proper cleaning repair can be effectively made on surfaces that have been exposed to aircraft environment as well as on new clean surfaces.

Material removal is also feasible. Controlled removal from a predetermined area is achieved by a chemical softening and scraping. Total removal is also achieved by a chemical treatment, followed by a mechanical removal, or by a mechanical removal alone. Water jet, plastic bead and carbon dioxide pellet equipment can be effectively used. A choice of such equipment is available on the market.

CONCLUSION

The sprayable integral fuel tank is applicable not only to fighter/attack aircraft but also to tankers, transports, commercial and general aviation aircraft. It has the potential for incorporation into aircraft in active service through a retrofit program. When a conventional bladder is replaced with a spray-sealed integral fuel tank concept, several benefits are realized.

The significant benefit is an increase of the usable fuel volume in a fighter/attack aircraft by an average of 7.4 percent. Concurrently, the weight of the fuel containment system is reduced by 25 to 50 percent. These values are a function of the tank size, complexity, geometry, and the sealant material utilized.

Most importantly, the eight years of research directed towards development of sprayable integral tank sealing technology have conclusively proven the feasibility of this approach. Numerous structural tests have demonstrated that the new system will successfully compete with any fuel tank sealing techniques presently in existence. In fact, based on USAF tests using the same components and the same environmental and load conditions, this system provided the best results of all (Figure 25).

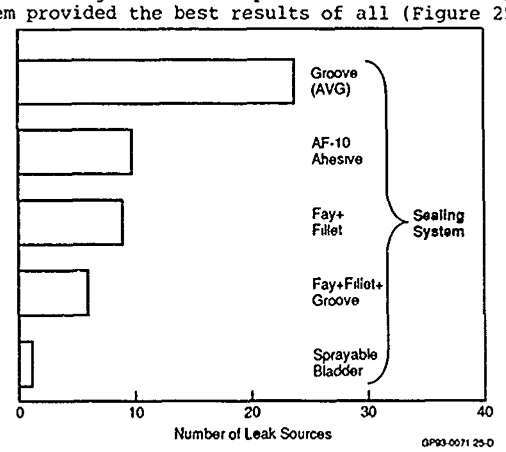

Figure 25. Performance Comparison of Integral Fuel Tank Sealing Systems

The order of magnitude better performance demonstrated in these sub-scale component fatigue tests forecasts a significant improvement in aircraft reliability, maintainability and supportability, with a potential to reduce the life cycle cost. The spray sealing system is also much more forgiving to assembly fit-up and workmanship requirements than any present system in use. At the same time efficient application techniques project a reduced production cost.

Development of the ballistic damage reduction methods compatible with the fuel containment and self-sealing materials also promises advantages. Initial tests indicate a marked ballistic damage reduction, which results in improved survivability of the aircraft.

Spray sealing applications have been used in Structural Dynamic Research to reduce dynamic response and fatigue. These treatments were found to help control damage extent and reduce leakage in Hydraulic Ram (Ballistic) work. Likewise, in other work, acoustic fatigue tests showed greater durability when panels were coated with spray-on elastomers. Here the added damping reduced response, thus fatigue was reduced (Ref. 1).

REFERENCE

1. Ferman, M. A., Healey, M. D., "Analysis of Fuel Tank Dynamics for Complex Configuration," AFWAL TR-87-3066, Nov. 1987.

DESIGN PHILOSOPHY AND CONSTRUCTION TECHNIQUES FOR INTEGRAL FUSELAGE FUEL TANKS

by

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SUMMARY

The fuel tanks of modern military aircraft are designed as integral fuel tanks. The design features and sealing systems which have been adopted at MBB for integral fuselage fuel tanks, to satisfy the requirement for tightness during the entire service life, are presented. The design aim was to minimize penetrations into the fuel compartments and to reduce the probability of fuel leaks by the application of redundant sealing barriers. The adopted sealing systems for the sealing of internal metallic substructure, and to an outer CFRP skin are described. Selected sealing systems were tested in a representative sideskin test box in fatigue and the experience gained was introduced into the design of a fuselage sealing box to aircraft standard which was also tested in fatigue.
The representative fuel tank structure of the sealing box has been used to demonstrate accessability for repair and to proof that repair actions to the sealing system are possible with suitable equipment.

1. Introduction

Modern military aircraft with the requirement for high performance necessitate a design with integral fuel tanks to minimize mass compared to conventional design with bladder or self-sealing tanks. Integral fuel tanks have the advantage that they can be located in complex shaped areas, e.g. between air intakes, and offer an increase in fuel capacity by 10 to 15 % within the available space envelope. In addition, compartmentation of fuel tanks can be easier achieved to improve the battle damage tolerance of the fuel system.

The major disadvantage of integral fuel tanks is fuel leakage, and considerable attention has to be given to the selection of appropriate sealing systems and sealants to prevent leakage during service life. On current aircraft with integral fuel tanks continuously problems with leaks are experienced, which leads to unacceptable high maintenance cost during service. The investigation which is presented in this paper shows the extensive work performed in the design of an integral fuel tank, and the selection of appropriate sealing systems to avoid leakage and to reduce maintenance cost in service.

2. Design Requirements for Integral Fuselage Fuel Tanks

The design of an integral fuselage fuel tank is governed by the requirement for tightness. Whereas on integral wing tanks leaks can be detected in most cases by walk-around inspection, detection of fuel leaks in integral fuselage tanks is more difficult to be achieved, except for leaks to the outer surface of the integral tanks.

The bays located adjacent to the integral fuselage tanks are normally full with equipment which can be damaged, and furthermore there are "hot" bays, e.g. for APU and gun, where leaking fuel could result in severe safety problems. Especially for these "hot" areas MIL-F-383638 requires redundant barriers or fire walls for fire protection.

In case that integral fuel tanks are located around an air intake the fuel tank usually has to be drip tight, as leaking fuel could severly damage the engines or even cause intake fire. For the above reasons detection of a fuel leak in integral fuselage fuel tanks usually results in downtime of the aircraft.

Special requirements apply also to the sealant materials and their qualification, as the temperatures in fuselage tanks can reach almost 100°C due to aerodynamic heating and the use of fuel for cooling purposes. At these high temperatures currently available sealing materials are at the upper end of their possible application. In addition, thermal stresses at the joints increase the loading for the sealing material and causes premature failure or leakage.

In case of leaks in fuselage integral tanks repair is rather difficult to be accomplished as access to the leaking area is usually not easy and the required maintenance actions are associated with high costs and non-availability of the aircraft.

3. Configuration of an Integral Fuselage Fuel Tank

The basic design concept of integral fuselage fuel tanks has been developed at MBB over several years. The integral fuel tank under consideration, Fig. 1, consists of four individual fuel sections. Each fuel section is further compartmentated by metall tank shear walls and tank floors into three individual fuel cells to improve battle damage tolerance. The inner boundary of the fuel tank is formed by the air intakes, which are manufactured from integrally stiffened plate by a stretch forming process, and the metallic tank floors. The air intake segments extend from one bulkhead to the other, thus reducing assembly costs and number of fasteners which could contribute to fuel leakage. The outer skin is a monolithic CFRP skin with cocured stiffeners. This design has been selected to minimize the skin mass, to save costs and time in assembly, and to reduce the risk of fuel leakage by a smaller number of fasteners required for assembly.

4. General Sealing Requirements

The sealing concept for fuselage integral tanks which has evolved at MBB by the subsequently described tests is based on the following sealing requirements:

- o Tank boundaries to outer structure have to be sealed by three redundant sealing barriers.
- o Tank boundaries within fuel tank areas have to be sealed by two redundant sealing barriers.
- o All bolts have to be wet installed.
- o Repair has to be easily accomplished, and therefore repair, preferably from outside, must be possible and good access to fuel tanks has to be provided.

The sealing methods and the types of sealant which are applied to achieve these requirements are presented in more detail in subsequent paragraphs.

5. Accessability and Repairablity

Originally the outer CFRP skin was designed without access covers and the only repair possibility was injection of sealant into the incorporated sealing grooves. In the course of development of the sealing test box, production and maintainability aspects resulted in the introduction of access covers to each fuel compartment (Fig.1).

A wooden mock-up was used to demonstrate that access to all areas within the fuel compartments can be gained, and that repair actions, although sometimes rather difficult due to limited space, can be performed and observed with suitable equipment. Fig.2 presents some illustrations of the accessability to different fuel compartments and the structurally restricted space envelope for repair action.

For the repair of leaks in integral fuselage tanks different actions, depending on the leaking area, are defined in Table 1. The preferred solution is injection of sealant into sealing grooves from outside. If this repair action can not stop leakage, then the access covers will be removed and appropriate repair action will be performed locally to the leaking area.

6. Sealing Materials

The materials applied for sealing of integral fuel tanks are required to perform satisfactorily under severe environmental conditions. The sealants are exposed to relative high temperatures up to 100°C, to temperature cycles with associated thermal stresses, to relative high loading, e.g. during pressure re-fuelling, and to fuel respectively fuel/water mixture in the sump of the fuel tanks. Under these harsh conditions the sealants have to show adequate strength and adhesion to the substructure over the entire service life. For the above reasons the selection and qualification process of proper sealing materials necessitates considerable attention.

6.1 Qualification Process

Available sealants for the considered applications are usually tested to a reduced screening programme in order to reduce the number of products for the qualification process. In the qualification programme the following parameters have to be determined:

- Processing parameters, amongst those are processing time, viscosity, application process, curing time and number of layers required to achieve specified sealing thickness.

- Mechanical properties, like tension strength, peel strength, elongation, hardness, and adhesion to different materials/surface treatments under fuel tank relevant conditions.

- Chemical stability against dry heat, fuel, fuel water mixture and contaminants.

- Physico-chemical properties, e.g. to determine the composition of material for Health and Safety clearance and for quality assurance purposes, and to investigate thermal stability of the sealant.

All sealants applied for this investigation were tested to the above requirements and were expected to meet these requirements.

7. Sideskin Test Box

7.1 Configuration of the Sideskin Test Box

For initial evaluation of the proposed sealing systems a simplified test box roughly representing the outer fuel cells between the tank floors and the tank shear walls (Fig.3) was designed. The test specimen (Fig.4) consisted of a 4 metres long and 1,2 metres wide box type substructure with three fuel compartments. The outer skin was manufactured as a continuous CFRP skin with cocured stiffeners. The metallic substructure, i.e. the box side walls and floor were built from steel, whereas the bulkheads were double sided milled Aluminium parts. To investigate different material combinations the upper side wall longerons to the CFRP skin were manufactured from CFRP on one side and from Titanium on the other side.

Load introduction to the test box was achieved via Titanium fittings attached to the four bulkheads. Accessability for inspection and repair was provided through load carrying covers in the box floor.

7.2 Sealing System

The sideskin test box was used to evaluate the effect of different sealing systems and material combinations. The test section in the centre part of the box was divided into four equal areas where different sealants and sealing methods were applied in these areas.

The sealing methods are summarized in Fig.5 and sketches of the individual sealing system together with a description of the applied sealing method are shown in Figs. 6 to 13.

7.3 Leak Detection

In general the origin of a fuel leak can not easily be located, as the place where leakage is first observed from outside usually does not coincide with the internal origin of the leak path. To determine the exact location of leaks at their entrance side basically two methods were applied.

Initially a method by pressurisation of the fuel tank with water was used to determine the presence of leaks by a drop in applied pressure and visual inspection for wetted areas from outside. As this method showed quite unsatisfactory results in location of leak origins it was dropped subsequently. Improvements in the detection of leaks were achieved by applying vacuum to the tank section in combination with dye penetrant application along the outer joints. This method enabled the correct location of the internal leak entrance but showed the disadvantage that dye penetrant could hardly be removed from the leaking area where it subsequently caused problems with the adhesion of repair sealant.

For these reasons the use of dye penetrant was omitted and the method was modified such that the tank area was dried thoroughly and, after application of vacuum, leak origins could be located as wetted areas due to the remaining liquid inside the leak path.

7.4 Loading

The box was tested under fatigue loading with superimposed temperature and pressure cycles. The fatigue spectrum was derived from a block of 200 flights with eight different mission profiles. This loading block was repeated consecutively until the required 18000 simulated flights were achieved. The maximum fatigue loads applied were ± 330 kN in torsion and 348 kN in bending.

During the test the box was filled with water and the temperature cycle according to Fig.16 was applied. This temperature cycle was repeated every two hundred simulated flights.

Tank pressurisation was simulated in accordance with Fig.15 and normally tank pressures reached 55 kPa, but every hundredth flight the tank pressure was increased to 73 kPa either at room temperature or at 90°C.

7.5 Test Results

7.5.1 Leakages in the Sealing System

Before the start of the fatigue test, the sealing system of the sideskin test box was tested with increased tank pressure of 120 kPa and tightness of the test section was successfully demonstrated. Nevertheless, during the first two hundred flights small leaks to the sidewalls and skin of the test box were detected in different areas.

After 400 flights the entrance locations of the leaks were determined by the methods described before and repair was accomplished by applying the same sealing materials as previously used. Usually it is not sufficient just to overseal leaking areas as leakage will occur again in these areas. Therefore the old sealant was completely removed from the leaking area and after thorough cleaning, fresh sealing material was applied.

Immediately after continuation of the fatigue test three leaks were realized. It was recognized that these three leaks resulted from the same leak entrance location, which had not been detected before, i.e. at the joint of the CFRP skin to the CFRP longeron to the aft bulkhead. Two further leaks resulting from one leak entrance occured after 1800 and 2100 flights. For these reasons the sealing system of the box was repaired again after 2600 flights.

During continuation of the fatigue test no leaks occured up to 5400 flights, where leakage was observed at a previously repaired position. Two further leaks were detected after 9000 flights and the box was then removed from the test rig for repair after 11360 flights. After repair of the sealing system at the production site no further leaks were located up to the required 18000 flights.

7.5.2 Results of the Fatigue Test

After 7000 flights, damages in the steel dummy structure, like cracks in the corners of the test specimen and hole elongation, especially in the area of the access covers in the box floor, were detected. After 11360 flights the structural damages were repaired and for this reason the box was removed from the test rig. No further damages occured up to the required 18000 flights.

7.5.3 Residual Strength Test

On completion of the fatigue test a residual strength test without internal pressure was performed at a temperature of 90°C in the test section, which showed only a 4 % decrease in strength compared to a static reference specimen.

7.6 Conclusions from Sideskin Test Box

For detail analyses of the different sealing methods, the CFRP skin was removed from the test box. The analyses resulted in the following conclusions:

- The adhesion of PR1720 sealant applied for faying surface seals and in conjunction with release agent was relatively poor and shrinkage of the sealant was observed due to a relatively high solvent content. For these reasons areas sealed with PR1720 were rather leak sensitive and the cause of leakage was in most cases loss of adhesion of the sealant to the substructure. Cohesive failure which could be related to material properties was not found. Leaks occuring in PR1720 sealed areas could be terminated by injection of DC94/031 into the sealing grooves.

- The low viscous sealant PR 2902 applied as "sprayable bladder", showed poor adhesion to the substructure and could not prevent leakage.

- The sealant DC 94/031 which was used as injection sealant into sealing grooves showed good performance and prevented leakage properly in case of repair.

- Sealing surfaces at CFRP structures were exceptionally affected by adhesive failure of the sealants, and improvements of adhesion could only be achieved by improved surface preparation on the CFRP structure.

8. Fuselage Sealing Box

The results of the sideskin test box were carefully evaluated and the experience gained was introduced into the design of a full scale fuselage sealing box. The aim of the test were the verification of the sealing system for an integral fuselage fuel tank, the determination of accessability and the demonstration of repairability.

8.1 Configuration of Fuselage Sealing Box

The sealing box, Fig.16, representative of three lateral fuel compartments between two bulkheads, was approximately one metre long and two metres wide. The forward and aft bulkhead the tank floors, the shear walls, the air intake duct and internal structure were manufactured from Aluminium to aircraft standard. At the lower side the

box was closed by a dummy Aluminium floor with an access panel to allow for inspection of leaks. The outer skin of the sealing box was manufactured as a monolithic CFRP skin with cocured stiffeners and integrated CFRP longerons, Fig.17. Load introduction to the sealing box was possible via integrated lugs in the two bulkheads.

Accessability to the individual fuel compartments for inspection and repair of the sealing system was provided by access covers in the CFRP skin.

8.2 Sealing System

The installed sealing systems are detailed in Figs. 18 to 23 and are briefly described below:

- Sealing of the CFRP skin to the tankfloor (Fig.18) was achieved by three redundant sealing barriers, i.e. faying surface seal (PR 1750), fillet seal (PR 1750) and "sprayable bladder" (PR1750) up to 100 mm above the tank floor. The sealing groove along the tank floor longeron had been incorporated but had not been filled with sealant.

- Sealing of the CFRP skin to the bulkheads (Fig.19) was accomplished by faying surface seal using PR 1750 on the aft bulkhead and by Goretex U20 tape on the forward bulkhead, and by fillet seal (PR 1750) applied around the joint. The sealing groove was machined into the bulkheads but was not filled with sealant.

- Sealing of the CFRP skin to the upper tank shear wall longeron (Fig.20) was provided by faying surface seal (PR1750) and fillet seal (PR1750).

- The joints of the tank floor and of the tank shear walls to the air intake, Fig.21, were sealed with faying surface seal (PR 1750), fillet seal (PR 1750) and "sprayable bladder" (PR 1750) up to 100 mm above the joint.

- Sealing of the minor frame to the CFRP skin (Fig.22) was achieved by faying surface seal (PR 1750) and fillet seal (PR 1750).

- The top and right hand access covers in the CFRP skin were sealed by a rubber cord whereas the access panel on the left hand side was installed with Goretex U20 tape.

- All bolts were wet installed using PR 1750.

8.3 Sealing

The sealing materials and their application in the sealing test box are summarized in Table 2.

Some details of the actual sealing application to the test box are presented in Figs. 23 and 24 which show the oversealing of collars and the application of fillet seal which can be closely monitored, even in complex shaped areas, by a video system with glassfibre optics.

8.4 Proof Load Pressure Test

After complete assembly of the internal metallic substructure a sealing test by pressurisation of the air intake section was performed to allow the detection of leaks before final assembly. Several leaks were detected and rectified. When the box has been finally assembled a proof load pressure test with water at 90°C up to 130 kPa was carried out. Again several leakages were found and repaired. The proof load pressure test was repeated and, as no pressure drop was observed during half an hour, the box was accepted as liquid tight.

8.5 Loading

The sealing box was tested under fatigue loading with superimposed temperature and pressure cycles. For the loading spectrum the FALSTAFF programme with a maximum fatigue load of ± 400 kN in torsion and 1000 kN in shear was applied. The pressure cycling was the same pressure spectrum as for the sideskin box, 15. The temperature spectrum was modified thus that the temperature was linearily increased from 20°C to 90°C and subsequently decreased during one hundred flights, Fig. 14.

8.6 Test Results

The fatigue test of the fuselage sealing box has completed successfully 12000 flights of the reqired 18000 flights. Large deflections of the test box of up to 10 mm have resulted in fatigue cracking of some angles in the lower dummy structure and therefore the box has been removed for repair.

Only one leakage occured during the 12000 flights which was caused by a loosened bolt in one access cover and which could be rectified by tightening the bolt to the required torque moment. It has to be reiterated that the sealing groove provided for repairability has not been filled with sealant.

During the inspection of the box it was recognized that the sealant PR1750 used as "sprayable bladder" has almost completeiy lost the adhesion to the structure but no repair action was performed as this adhesion probiem was mainly attributed to the harsh test conditions in water.

After structural repair of the test box the fatigue test will be continued for another 6000 flights and no problems with leakage are expected as the sealing system has shown excellent performance up to now.

9. Conclusions

The test evidence on structural boxes has shown that the problem of fuel leakage of integral fuel tanks can be overcome by the selection of appropriate design features and sealing systems. The major advantages of the selected design are the reduction of penetrations into the fuel tank which accordingly reduce the risk of fuel leaks, and the use of independent sealing systems, which, even in case of failure of one sealing barrier still provide the necessary sealing capability.

It has been successfully demonstrated that fuel leaks in integral fuselage fuel tanks, can be terminated by injection of sealant into injection grooves. The incorporation of sealing grooves is associated with a mass penalty and increased manufacturing costs, however, these disadvantages have to be accepted in order to achieve a satisfactory sealing system which allows for repair from outside without extensive maintenance action and associated high cost in service.

Acknowledgement

The authors gratefully acknowledge the German Ministery of Defence for the financial support to the programme and the work of the MBB specialists who have performed and analysed the individual test programmes.

References

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Entwicklung, Fertigung und Prüfung einer Integral-Tankbox
MBB/LKE234/KEL/R/014 31.12.1986

Leaking Area	APPLICABLE REPAIR METHODS	
	Repair From Outside (Preferred Method)	Access to Fuel Compartment Required
Leakage Into Internal Cavities	Reinjection of Sealant (DC 94/031) Into Sealing Grooves	Repair of Fillet Seal Through Access Panels And/Or Overspray of "Sprayable Bladder "
Leakage To Skin Through Bolts	Re-Seal of Bolt Heads Or Replacement and Wet Installation of Bolt	As Above
Leakage Between Tanks	Reinjection of Sealant (DC 94/031) Into Sealing Grooves	Repair of Fillet Seal Through Access Panels

Table 1: Repair Methods For Fuselage Integral Fuel Tanks

APPLICATION	MATERIAL	QUALIFICATION STATUS
Injection Groove	Q4-2805	Qualified
	DC 94-031	Qualified
Faying Surface Seal	PR1750B	Qualified
Fillet Seal	PR1750C	Qualified
Sprayable Bladder	PR1750A	Qualified
Access Panels	Goretex U20	Qualification in Progr.

Table 2: Sealing Materials For a Fuselage Integral Fuel Tank

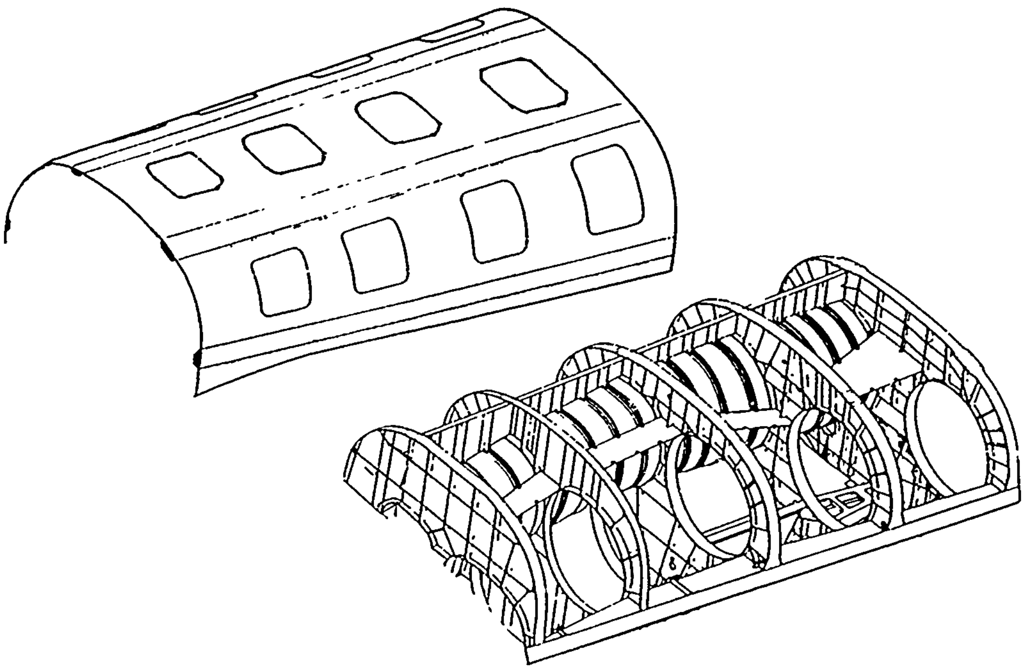


Figure 1: Configuration of Integral Fuselage Fuel Tank

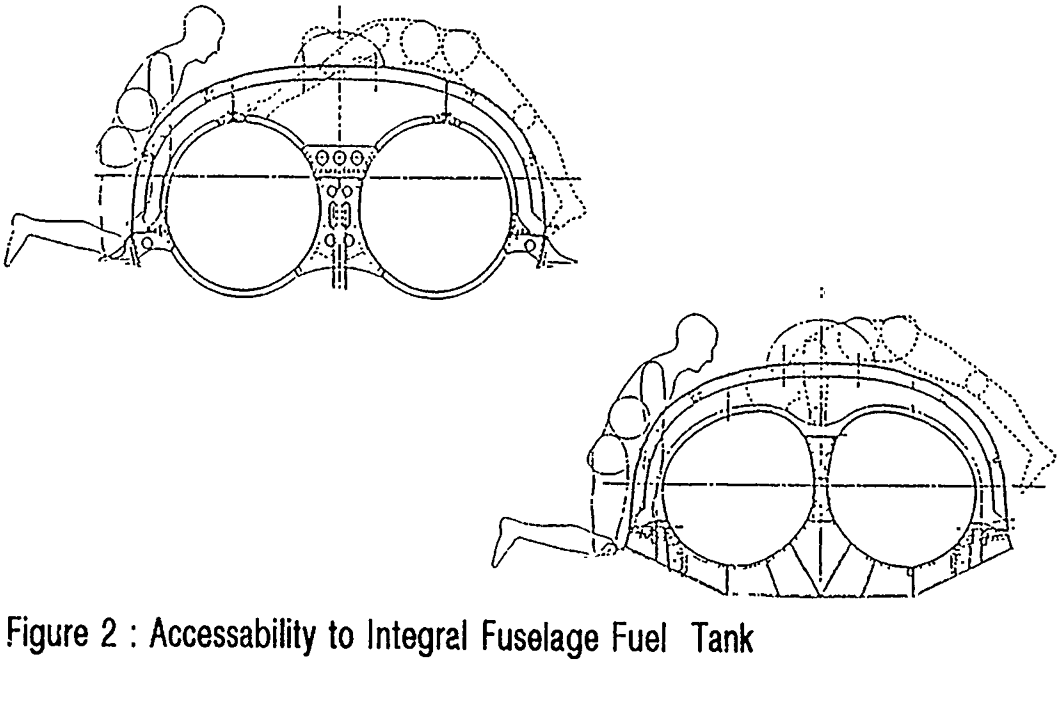


Figure 2 : Accessability to Integral Fuselage Fuel Tank

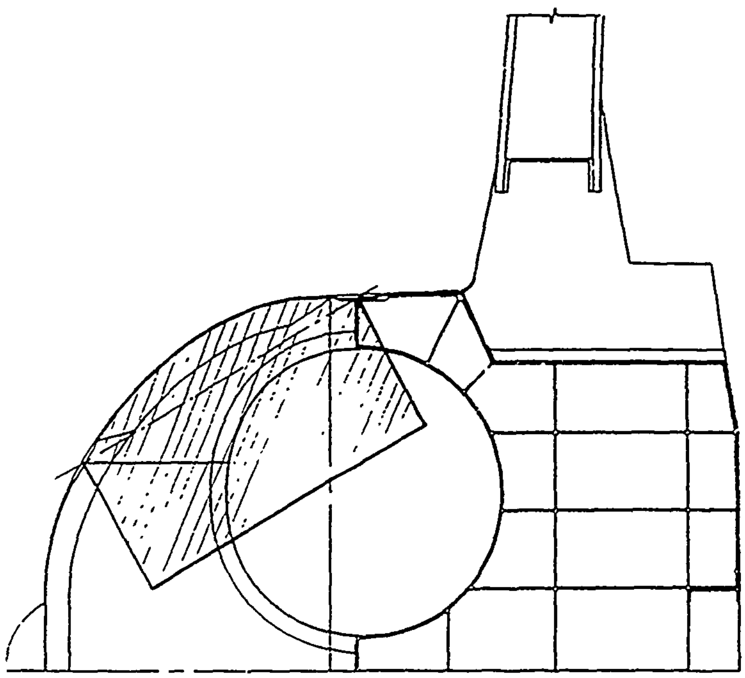


Figure 3: Extension of Sideskin Testbox

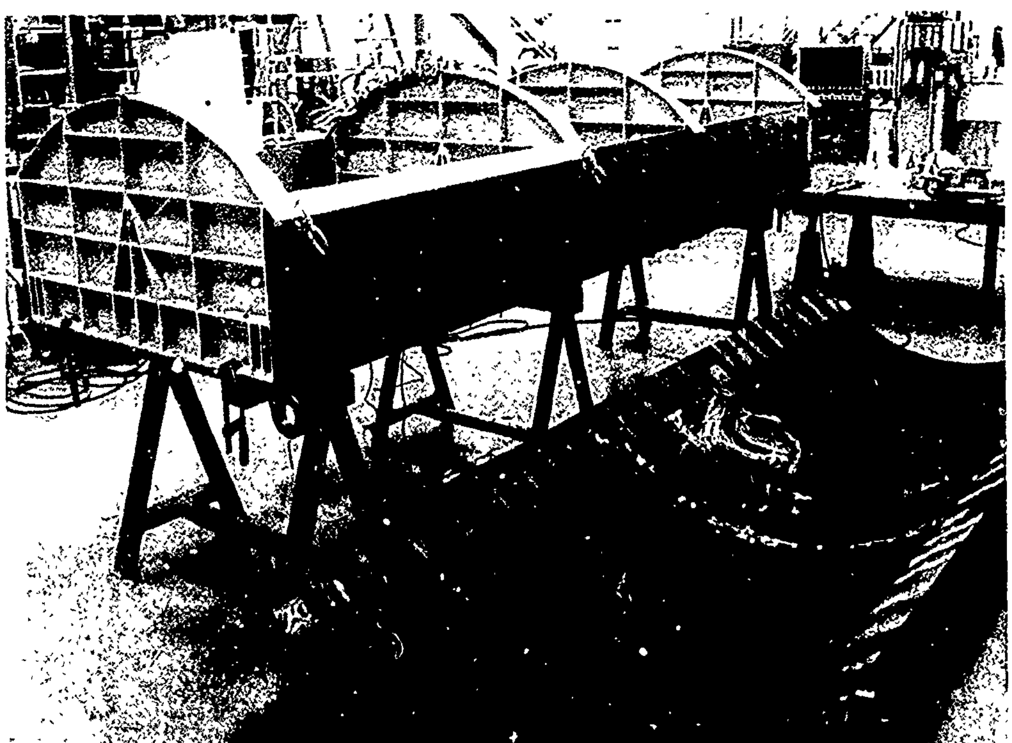


Figure 4: Sideskin Testbox Before Final Assembly

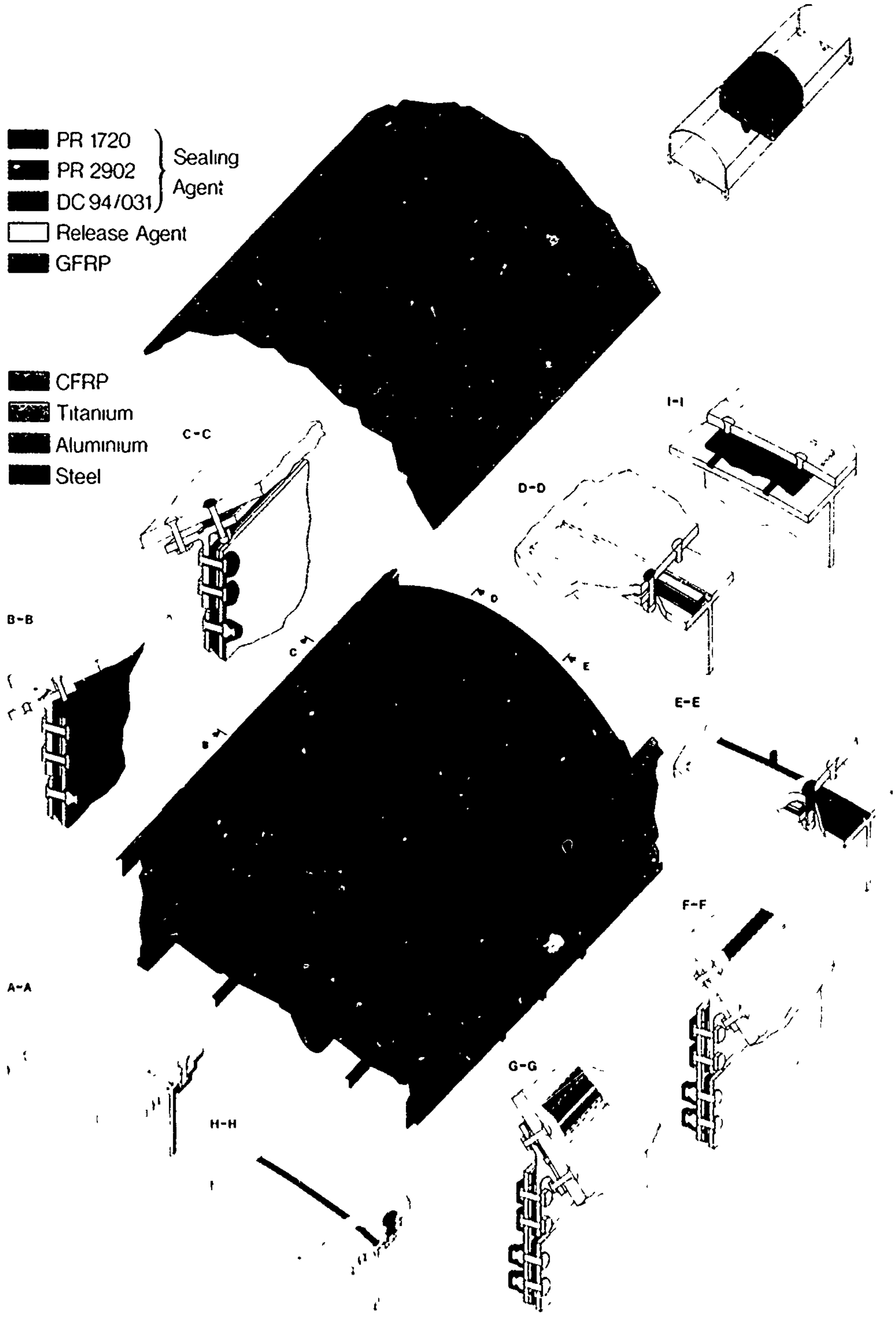
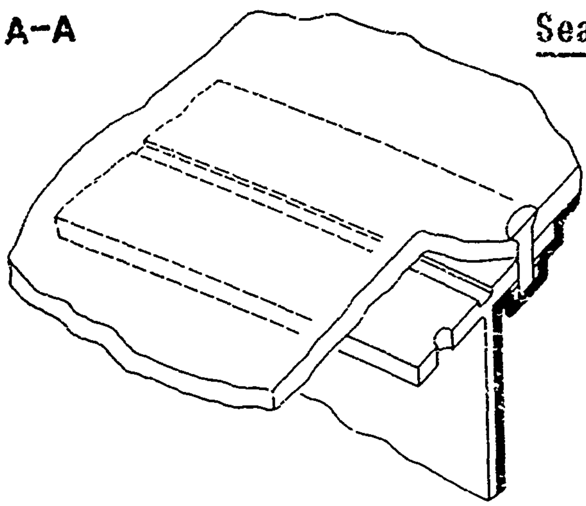


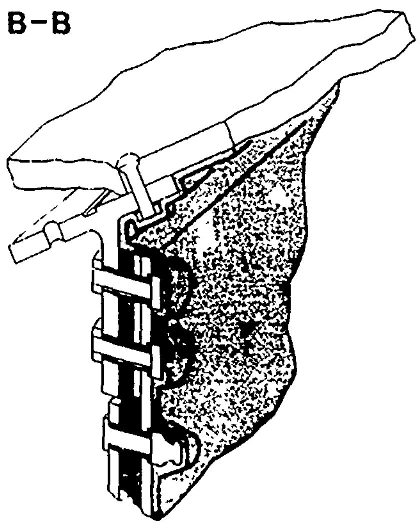
Figure 5: Sideskin Testbox – Sealing Systems



Sealing System Section A-A

- Joint oversealed with sprayable bladder PR 2902
- No faying surface seal
- Injection groove not filled
- Bolts dry installed

Figure 6: Sealing of CFRP Skin to Forward Bulkhead (RH Side)

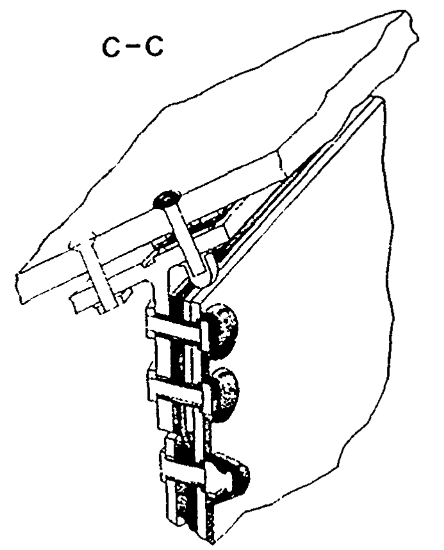


Sealing System Section B-B

- Joint oversealed with sprayable bladder PR 2902
- No faying surface seal
- Injection groove not filled
- Bolts dry installed

Figure 7: Sealing of CFRP Skin to CFRP Longeron (FWD)

C–C

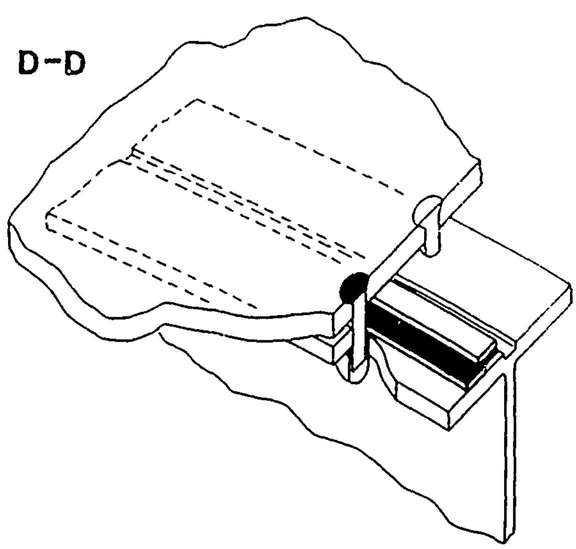


Sealing System Section C–C

- Faying surface seal with PR1720 between release agent
- Injection groove not filled
- Bolt heads sealed with PR1720
- Pressure tight anchor nuts oversealed with PR1720

Figure 8: Sealing of CFRP Skin to CFRP Longeron (AFT)

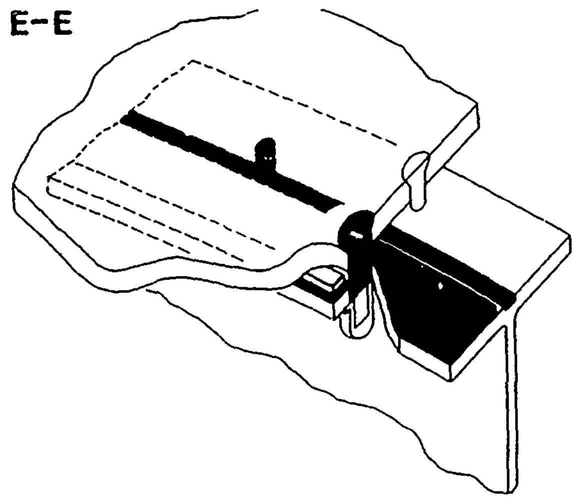
D–D



Sealing System Section D–D

- Faying surface seal with PR1720 between release agent
- Injection groove not filled
- Bolt heads sealed with PR1720
- Anchor nuts

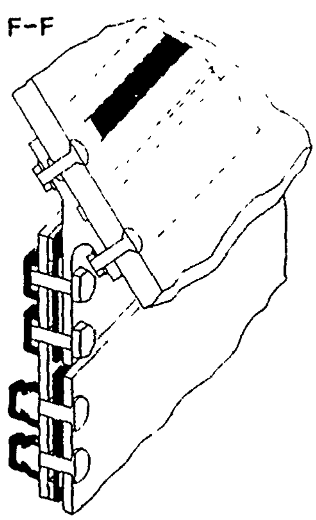
Figure 9: Sealing of CFRP Skin to Aft Bulkhead (RH Side)



Sealing System Section E-E

- Faying surface seal with PR1720 between release agent
- Injection groove filled with DC 94/031
- Bolts wet installed with PR1720
- Pressure tight anchor nuts

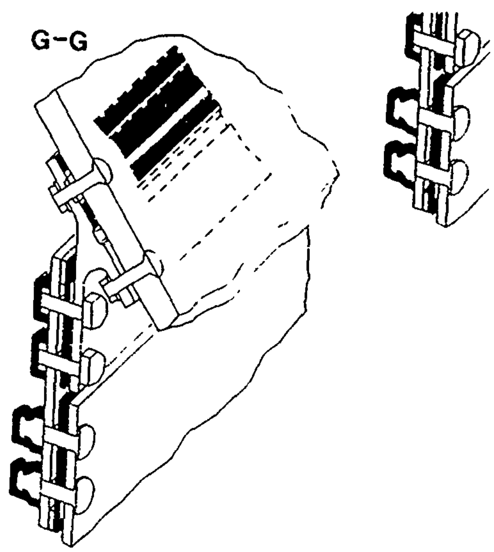
Figure 10: Sealing of CFRP Skin to Aft Bulkhead (LH Side)



Sealing System Section F-F

- Sealing groove at bolts filled with DC 94/031
- No faying surface seal
- injection groove not filled
- bolts dry installed
- collars oversealed with PR1720

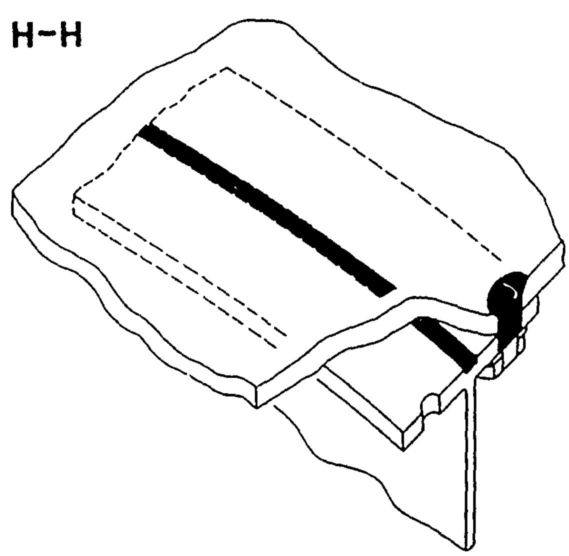
Figure 11: Sealing of CFRP Skin to Ti Longeron (AFT)



Sealing System Section G-G

- Faying surface seal with PR1720
- Sealing groove along bolts filled with DC 94/031
- Injection groove not filled
- bolts dry installed
- Collars oversealed with PR1720

Figure 12: Sealing of CFRP Skin to Ti Longeron (FWD)



Sealing System Section H-H

- No faying surface seal
- Injection groove filled with DC 94/031
- Bolts wet installed with PR1720

Figure 13: Sealing of CFRP Skin to Forward Bulkhead (LH Side)

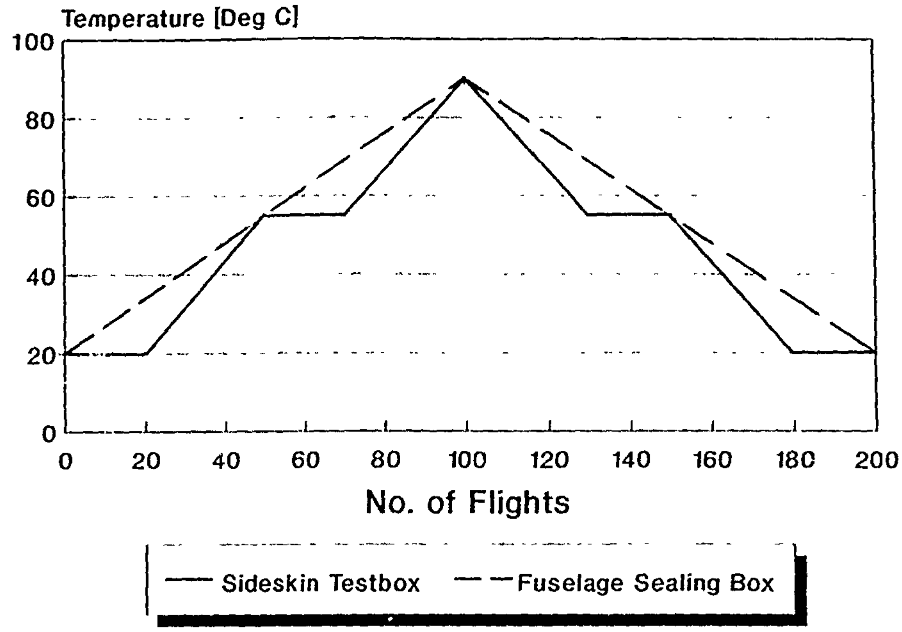
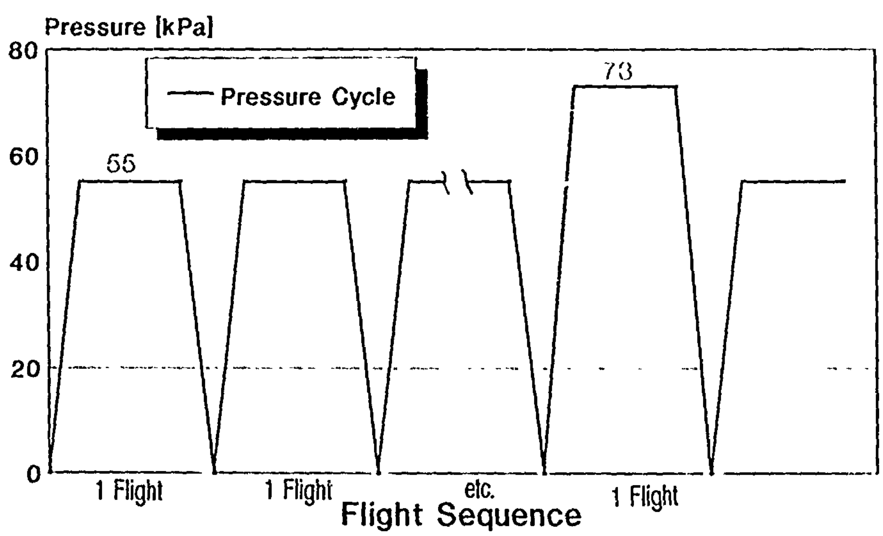


Figure 14: Temperature Cycle For a Block of 200 Flights



Increase of tank pressure to 73 kPa every hundredth flight alternating at RT and 90 Deg C

Figure 15: Tank Pressurisation Cycle

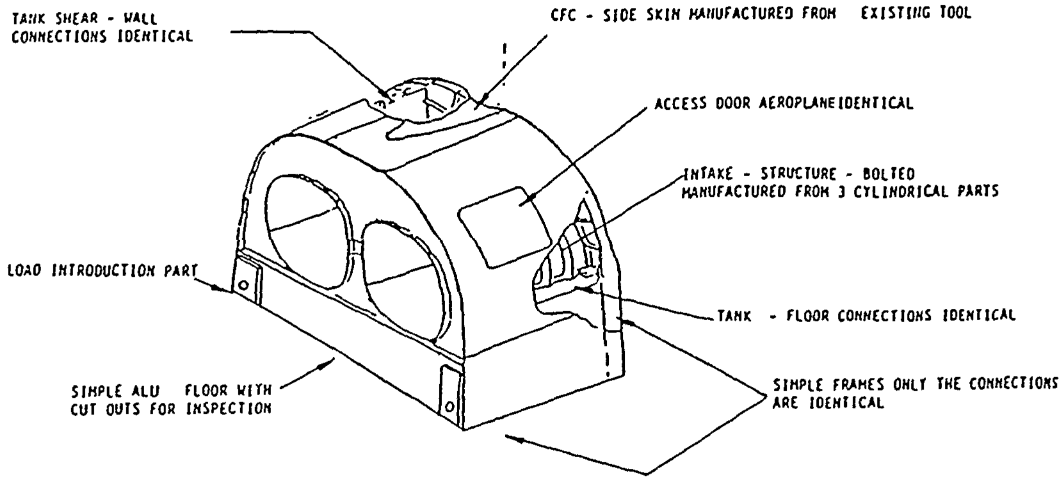


Figure 16: Basic Configuration of Sealing Testbox

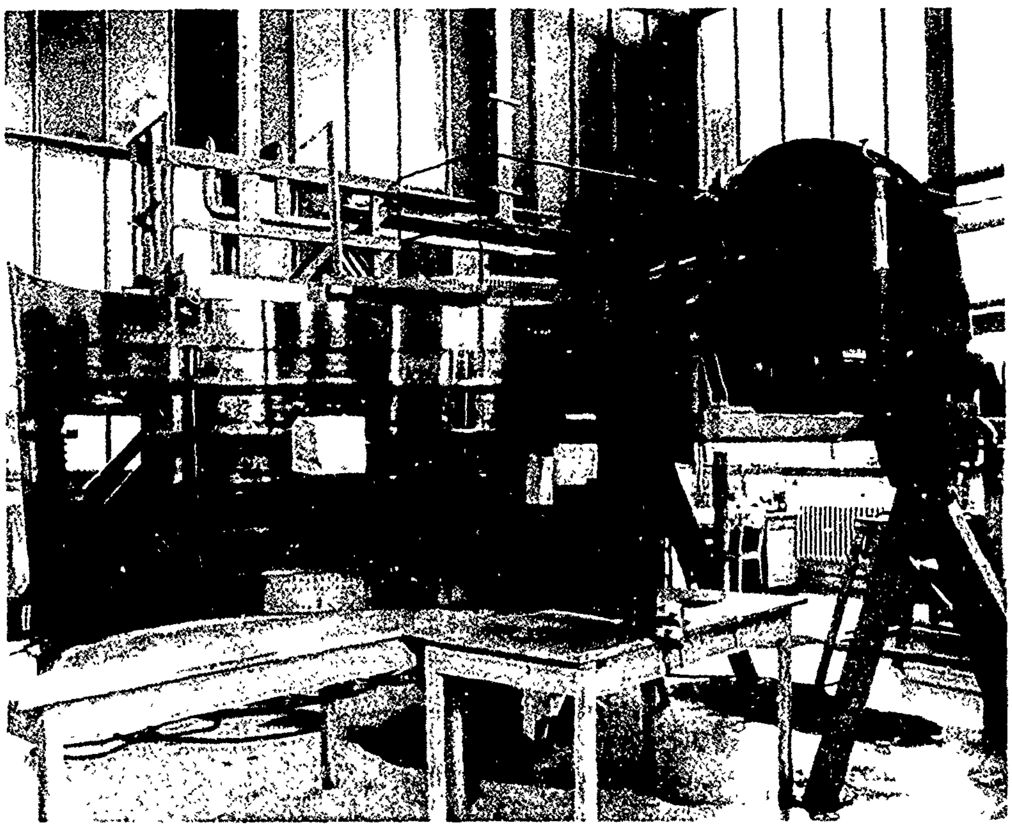


Figure 17: CFRP Skin With Co-Cured Stiffeners and Sealing Testbox Substructure

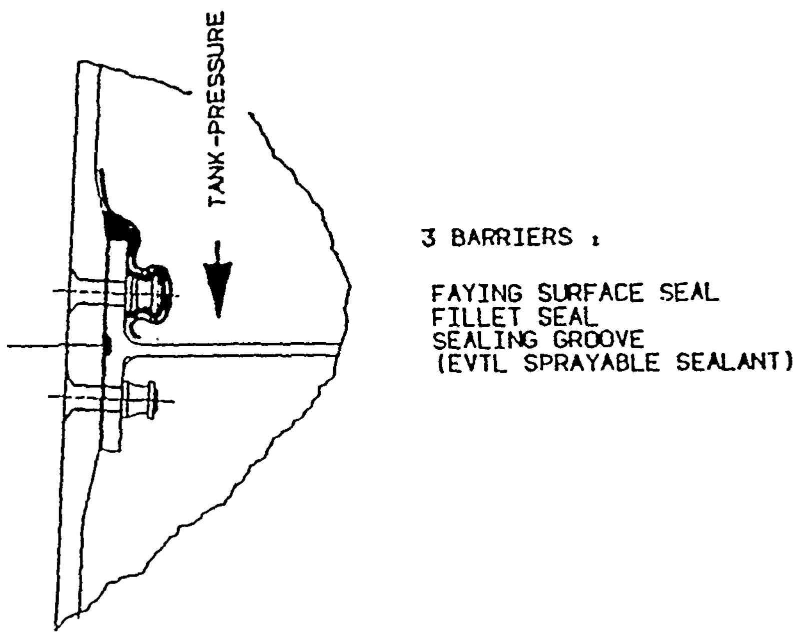


Figure 18: Sealing of CFRP Skin to Tank Floor

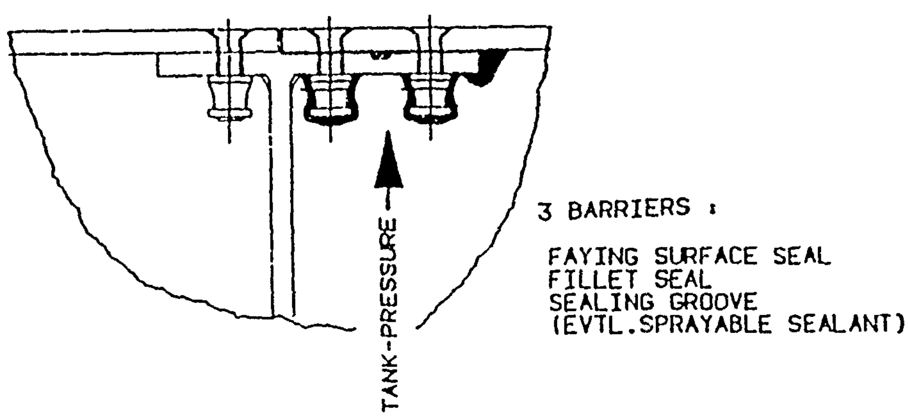


Figure 19: Sealing of CFRP Skin to Bulkheads

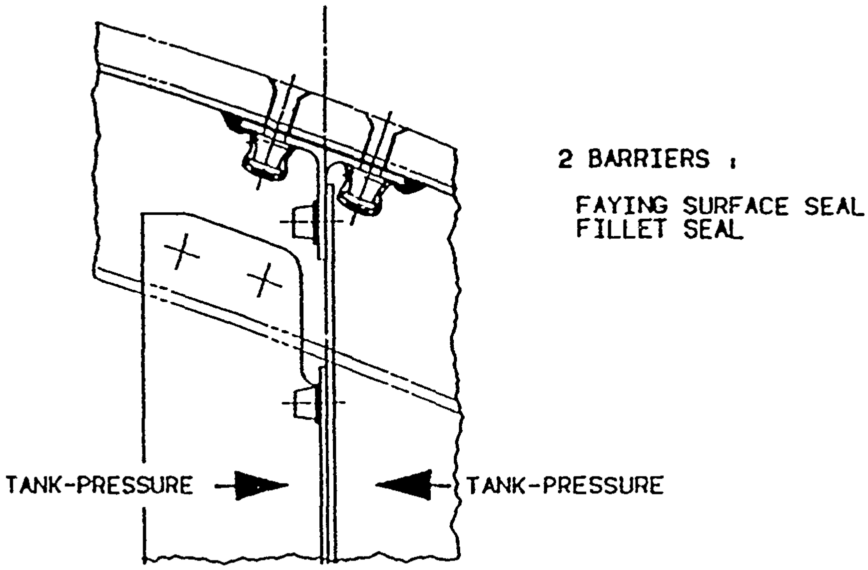


Figure 20: Sealing of Shear Wall Longeron to CFRP Skin

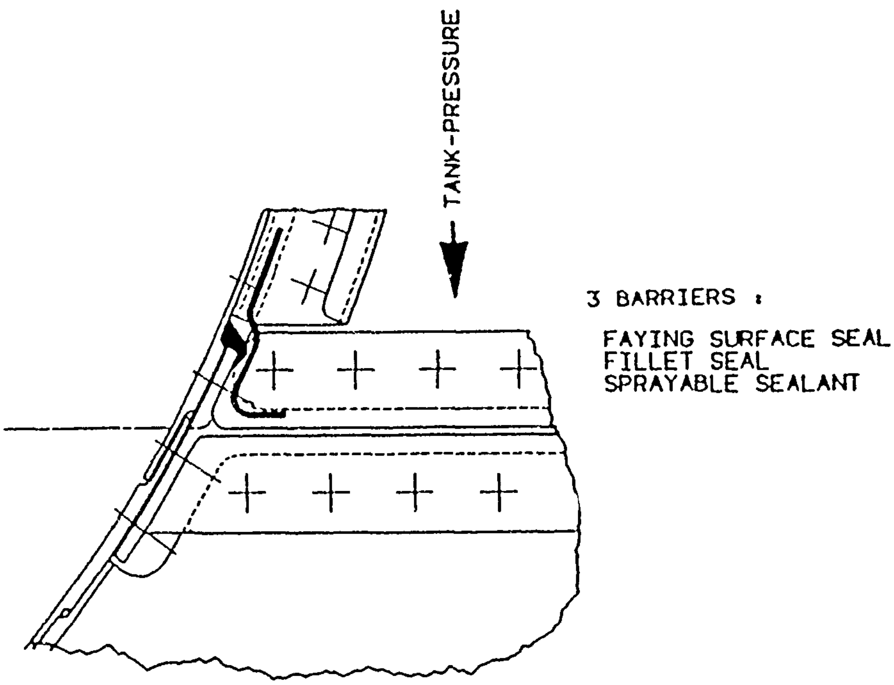


Figure 21: Sealing of Tank Floor to Air Intake

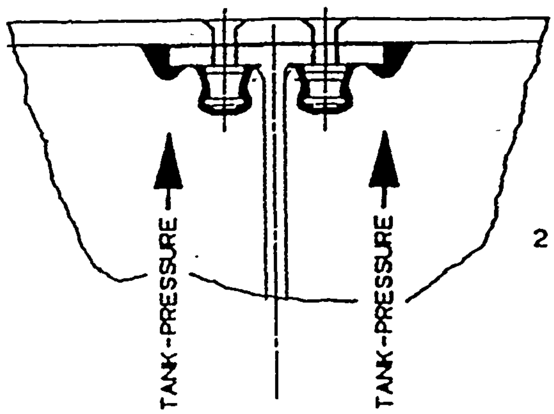


Figure 22: Sealing of Spectacle Frame to CFRP Skin

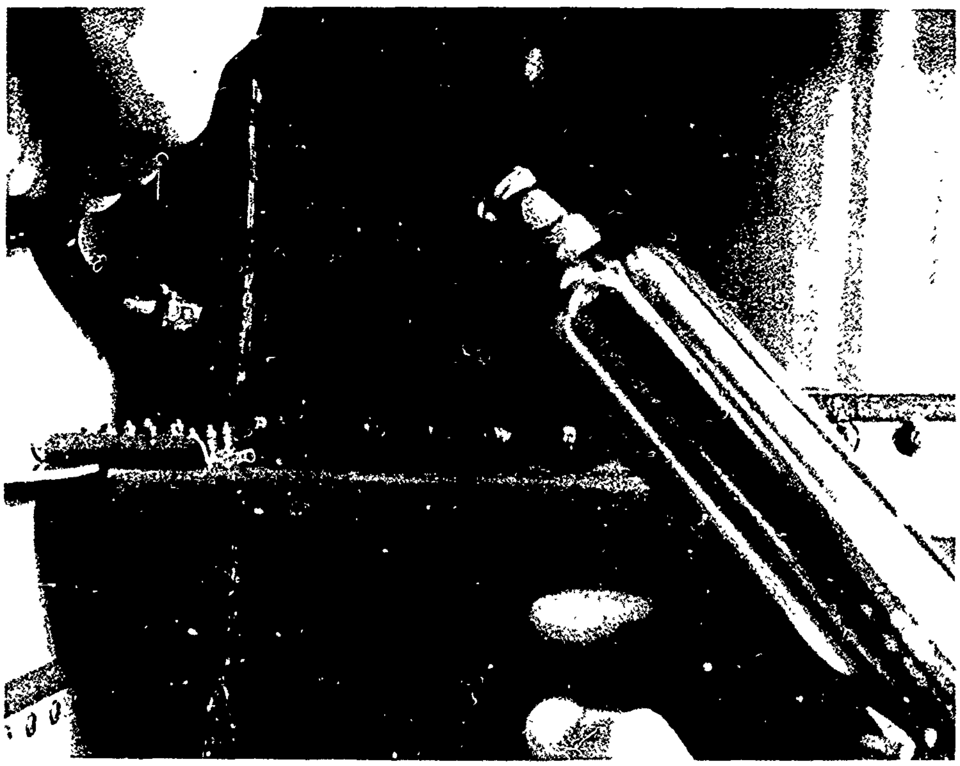


Figure 23: Sealant Application to Bolt Collars

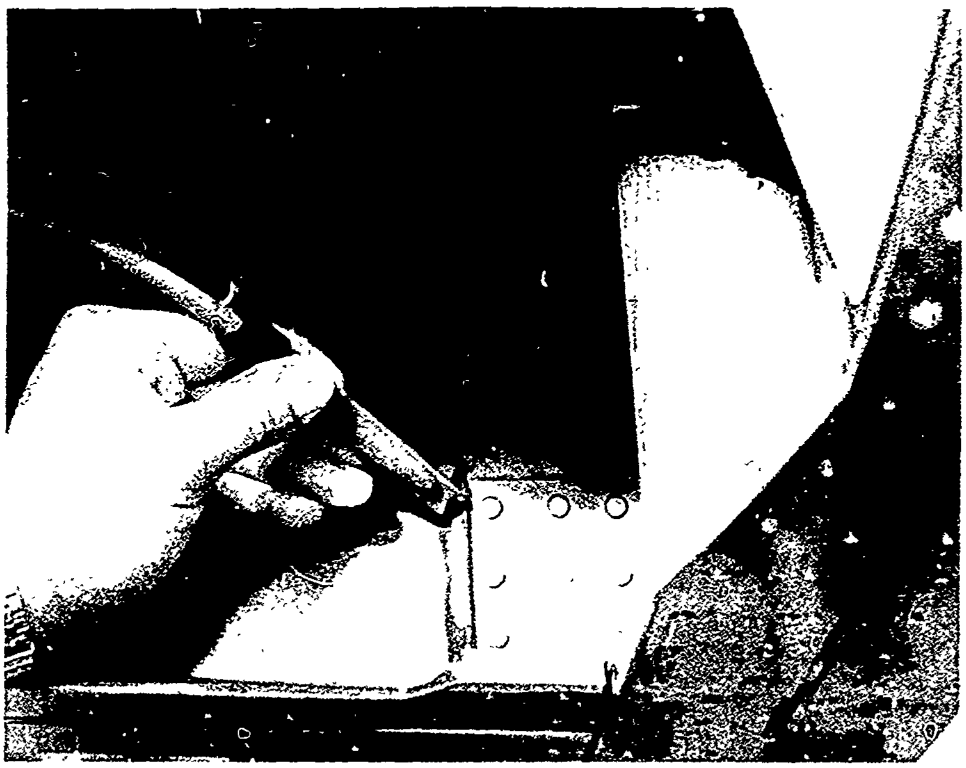


Figure 24: Application of Fillet Seal

FUEL TANK EXPLOSION PROTECTION

by

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SUMMARY

The modernization of military aircraft has included the addition of fuel tank fire/ explosion protection. A military transport, like any other aircraft, is susceptible to fuel tank explosions from a number of sources, including combat gunfire. Studies have shown that the fuel tanks are the largest single contributor to the vulnerability from high explosive incendiary (HEI) rounds for transport aircraft. Since no aircraft has the inherent capability to suppress flames within the fuel tank ullage, it is important to provide a tank explosion protection system that prevents fires and explosions inside the fuel tanks during all modes of aircraft operation.

The Lockheed Aeronautical Systems Company and the United States Air Force have acquired considerable knowledge about explosive suppressant foam through its use in the Lockheed-built C-130 aircraft. This foam material prevents or limits flame and pressure wave propagation and acts as an anti-slosh baffle. In-service experience with the foam will be discussed. Associated maintenance problems and impacts on man-hours, weight, and cost will also be reviewed. The status of the new foam materials being developed to eliminate electrostatic problems with the present explosion suppressant foam will be stated and assessed. Alternative techniques and methods to achieve fuel tank explosion protection have been proposed for the C-130 and will be compared to the performance of the foam installation. Finally, explosion suppression will be put into perspective with other C-130 wing modernization features.

INTRODUCTION

Aircraft fuel tanks are highly vulnerable to fire and explosion resulting from combat threats unless appropriate protection systems are incorporated. Explosion protection can be provided by reticulated foams, liquid nitrogen inerting, halon inerting, and onboard inert gas generating systems. The USAF has extensive experience with all of these fuel tank protection methods.

The USAF has used a reticulated polyester polyurethane foam successfully to suppress explosion and resulting fire in fuel tanks of C-130 aircraft (Figure 1) since the late 1960s. Initially, the foam was orange with a nominal 10 pores per inch and a

Figure 1. Lockheed C-130 Hercules

nominal density of 1.8 pounds per cubic foot. This material was susceptible to hydrolytic degradation which shortened its service life. Better materials with improved hydrolytic stability and lower weight were developed by the USAF and the foam supplier. A new foam material designated as "hybrid" polyether polyurethane foam, manufactured in blue colors, provided this improved hydrolytic stability resulting in increased service life. C-130 aircraft in the USAF inventory are currently equipped with this blue foam.

By the end of 1980, the USAF experienced ignitions in A-10 aircraft fuel tanks and shortly thereafter in C-130 fuel tanks. It was determined that the blue foam has an electrical resistivity of several orders of magnitude greater than the original polyester foams. The blue foam acts as a capacitor and builds a static charge of some 8000 to 12,000 volts that can result in an electrical discharge between the foam and fuel tank components. While no aircraft were lost or serious injury incurred, there was enough concern to cause development of conductive safety foams. Two types were developed. One is a post-treated conductive foam using an additive, and the other is an "in-situ" foam. This latter material has the conductive properties built into the resin system and appears to offer the most cost-effective approach to the problem.

While no decision has been made on the optimum type of conductive foam, this technology is close to being incorporated on military aircraft. A decision has been made to retrofit the A-10 aircraft with conductive foam, and it is likely that the C-130 will be retrofitted also.

The ramifications of using explosion suppressant foams in C-130 fuel tanks will be reviewed and associated technology discussed.

C-130 EXPLOSIVE SUPPRESSANT FOAM EXPERIENCE

Foam used as fire/explosion suppression filler material in C-130 aircraft fuel tanks is a low-density, reticulated polyether polyurethane in which virtually all membranes are eliminated from the conventional strand and membrane structure. The USAF procures it per Military Specification MIL-B-83054B.

Foam acts as an explosion suppressant when installed in fuel tanks because it:

1. Acts as a heat sink - absorbing heat - reducing temperature at spark point.
2. Breaks up compression waves that precede the flame front in an explosion.
3. Has high surface-to-volume ratio that enables the strands to collect a fine film of fuel, thereby enriching the vaporous mixture in the unfilled portion of the tank. (This characteristic tends to provide a rich mixture in the case of JP-4 fuels, but tends to enrich a normally lean mixture of JP-5, JP-8 fuels.)

Several different types of foam with varying porosity and density are identifiable by their color, as shown below:

Type	Color	Density (Lbs/Ft3)	Porosity (PPI)
I	Orange	1.7 - 2.0	7 - 15
II	Yellow	1.2 - 1.45	8 - 18
III	Red	1.2 - 1.45	20 - 30
IV	Blue (dark)	1.2 - 1.45	8 - 18
V	Blue (light)	1.25 - 1.45	20 - 30

Types I, II, and III are produced from a polyester material. Types IV and V are a copolymer material consisting of polyether and polyester. The foam used for an aircraft application depends on the assumed foam kit design selected for that particular aircraft. In general, the high porosity foams (Types III and V) are used for fighter aircraft while Types I, II, and IV are used in transport applications. The principal C-130 experience to date is with the Types I, II, and IV materials. Numerous tests by the USAF and others have proven the foam capable as a fuel tank protection medium.

Lockheed Aeronautical Systems Company (LASC)-Georgia has delivered more than 1900 C-130 aircraft to 61 nations. Of these, 54 production airplanes were delivered from 1968 to 1970 with foam designed and fabricated by LASC-Georgia installed in the fuel tanks. The foam was installed for protection against small arms fire in Vietnam. Since 1983, some 85 new production C-130 airplanes have been delivered with USAF-furnished foam kits installed. Additionally, foam has been installed in about 500 USAF in-service C-130 aircraft by other contractors.

Initially, these aircraft were equipped with the Type I, orange foam made of a polyester material. This foam proved to have a short service life, less than two years in the hot, humid condition of Southeast Asia. The foam would revert to a liquid or mastic condition. The mastic reversion is caused by hydrolytic instability or lack of resistance to high humidity conditions and resulted in loss of inerting capability due to foam collapse in the tank. Also, this orange foam tended to break up at cold temperatures, resulting in fuel system and engine filter contamination from foam bits and fibers. As a result, after the Vietnam conflict, the foam was removed from most of these C-130s, although it still remained in some special mission aircraft.

Because of these problems with the polyester foams, a new series of reticulated foams were developed of copolymer materials, predominantly polyether. These blue foams (Type IV and V) are several times more resistant to water, humidity, and temperature in terms of service life. These polyether foams are also lighter weight than the polyester foams. For these reasons, the USAF began to use Type V, fine porosity, blue foam in the tanks of fighter aircraft and Type IV, coarse porosity, blue foam in special-purpose C-130 aircraft. At that time as well as now, there were no electrostatic design requirements or goals for either of the foam types. Lab tests have shown that the blue polyether foams could have more than 10 times the discharge energy than the polyester foam previously used for inerting.

Retrofit of the special-mission C-130 with the Type IV, coarse, blue foam began around 1977. In the experience of Lockheed Aircraft Service (LAS) Company, no problems with this blue foam have developed. Several LAS-installed blue foam C-130s have been in service since 1977 with no apparent problems.

In 1981, therefore, the USAF decided to install the Type IV blue foam in all USAF C-130 aircraft, both those in-service and in new production airplanes. Using blue foam prototype engineering and installation information generated by LAS in 1977, Warner Robins ALC (WR-ALC) proceeded to develop and fabricate blue foam lots for installation in C-130 aircraft. A Safety Time Compliance Technical Order (TO 1C-130-1063) was issued in June 1982 to install this Air Force foam kit.

The standard C-130H has four integral wing tanks, two auxiliary fuel tanks, and two external pylon tanks (see Figure 2). The total C-130H fuel capacity is 9800 gallons. Foam was installed in all of the tanks. The size of the access opening into the tank essentially established the size of foam piece that could be installed in that tank. Figure 3 illustrates the complexity of installing the foam in the tank due to the large

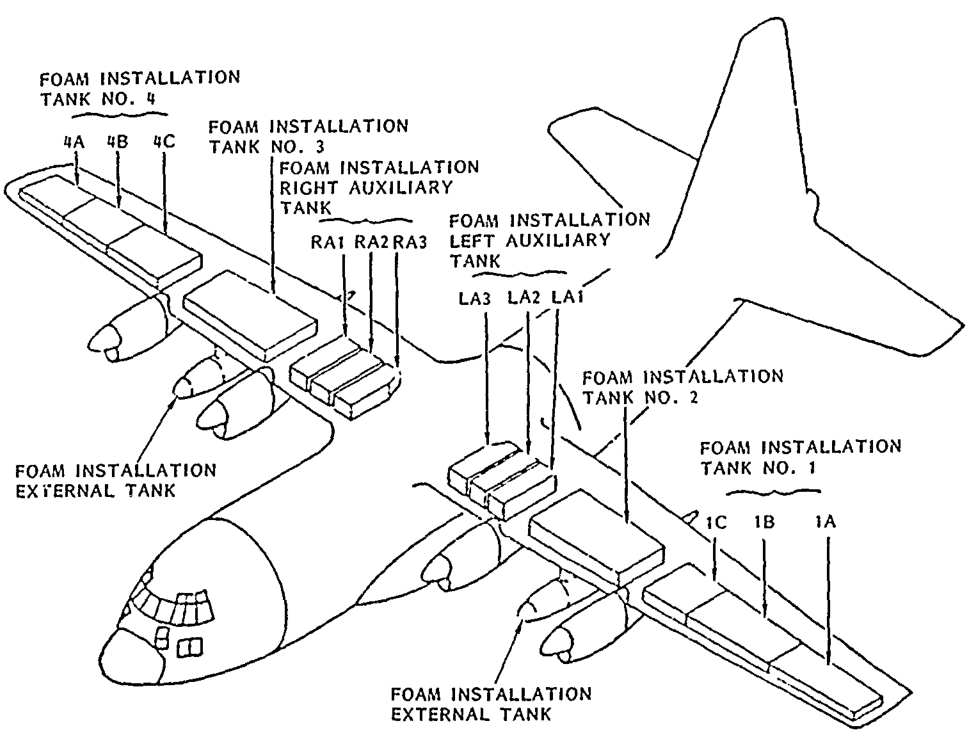

Figure 2. C-130H Fuel Tank Arrangement

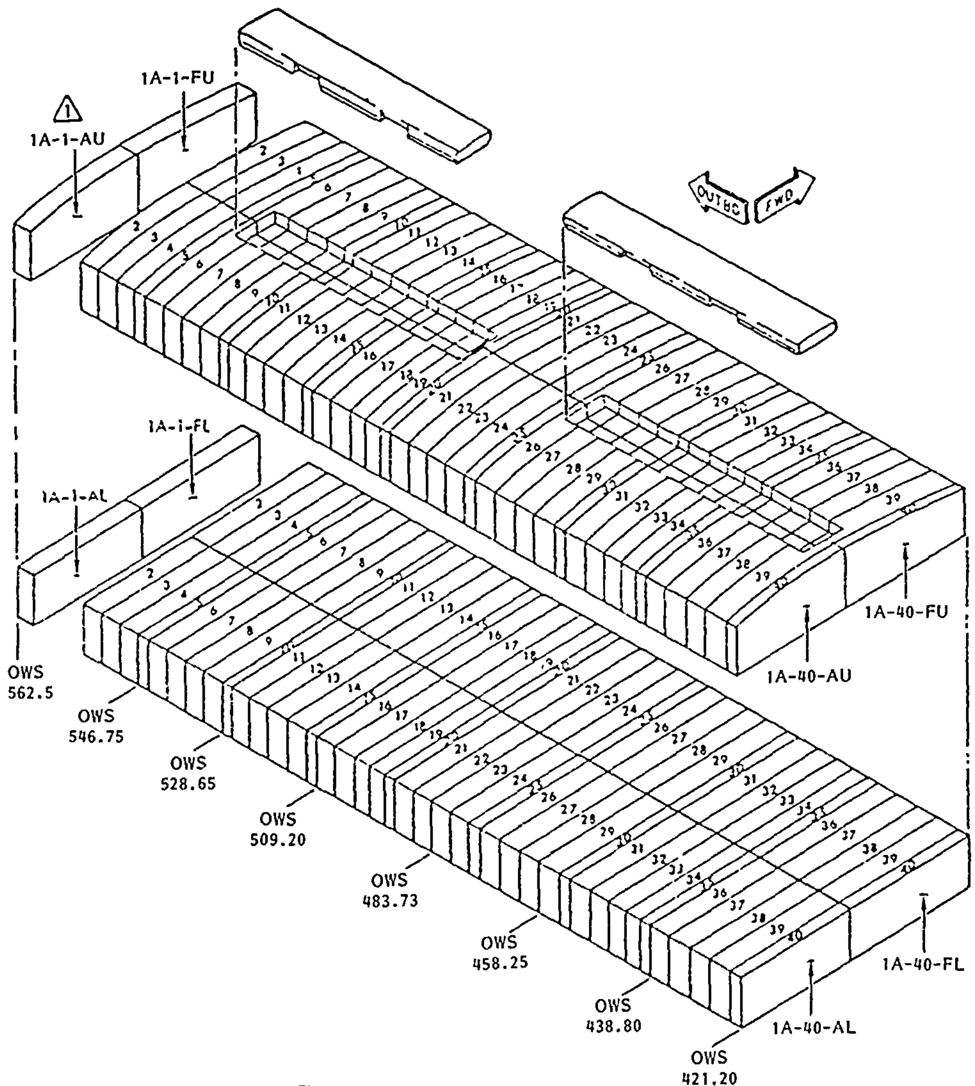

Figure 3. Typical Foam Installation

number of pieces required. Note that this figure shows only the number of foam pieces (150) needed to fill the outboard main tank. The entire aircraft requires 1540 pieces for the wing tanks and 152 pieces for the pylon tanks. The physical configuration of the fuel tanks require cutting some of the foam pieces in rather odd shapes to fit the contours of the structure. The foam is installed with zero compression and rests on the bottom skin structural risers, just touching the top skin risers and fore and aft spars. The foam kit has about 15 percent by volume vacant spaces (voiding) achieved by selectively locating four and one half-inch diameter voiding holes throughout the foam kit and by cutting large openings around tank plumbing and components to prevent interference impacts.

The total volume of foam installed is the gross volume of the fuel tank less any voiding. For the C-130H, the foam volume is 1148 cu. ft. and weighs 1543 lbs. The usable fuel lost when foam is installed in the C-130H is 216 gallons displaced by the foam baffles and another 216 gallons that cling to and are retained by the foam, for a total of 432 gallons or 2808 pounds of fuel unavailable for a mission.

The installation of foam has no real effect on normal fuel system operation and the foam itself is virtually maintenance free. However, the presence of foam in the fuel tank greatly impacts the removal/replacement of in-tank components. Time to remove, store, and reinstall the foam baffles must be added to the normal time necessary for fuel system components maintenance. Foam indeed has an impact on normal C-130 maintenance time and costs (Foam adds approximately eight hours per tank to maintenance time).

Figures 4 through 9 depict the blue foam applications to the C-130 wing and external fuel tanks.

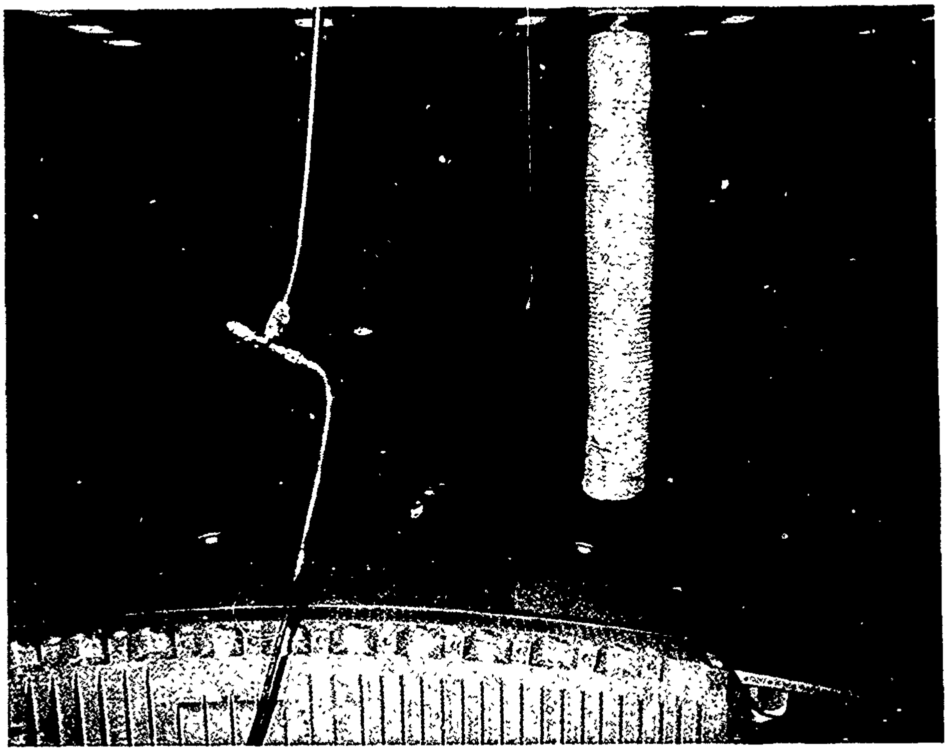

Figure 4. C-130 Outer Wing Surface

Figure 5. Interior Tank Structure

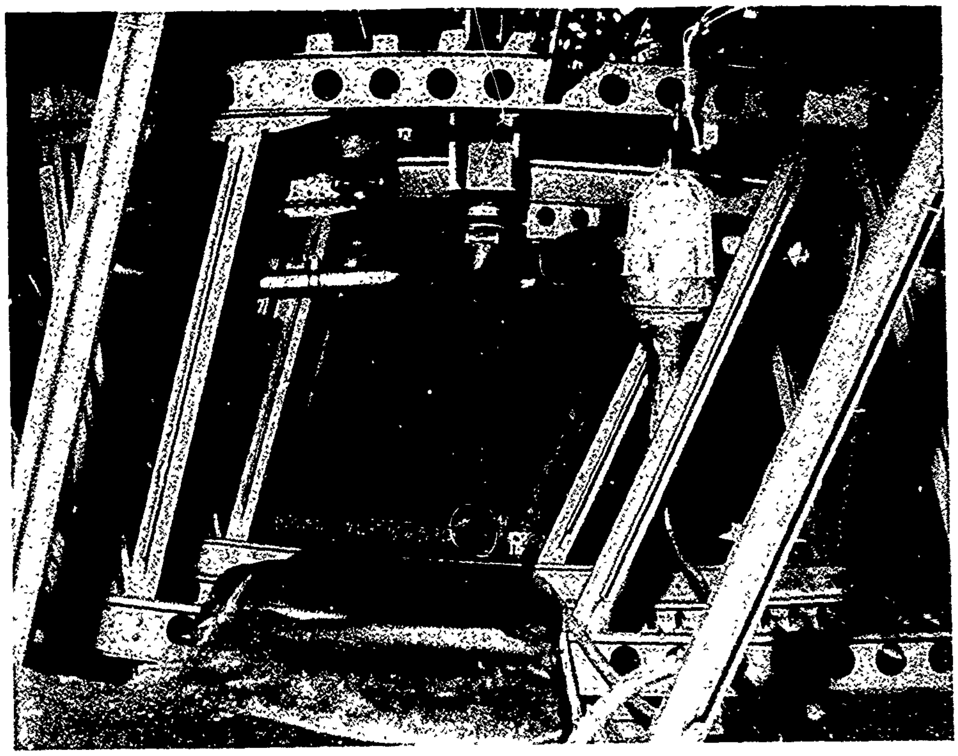

Figure 6. Blue Foam Installation

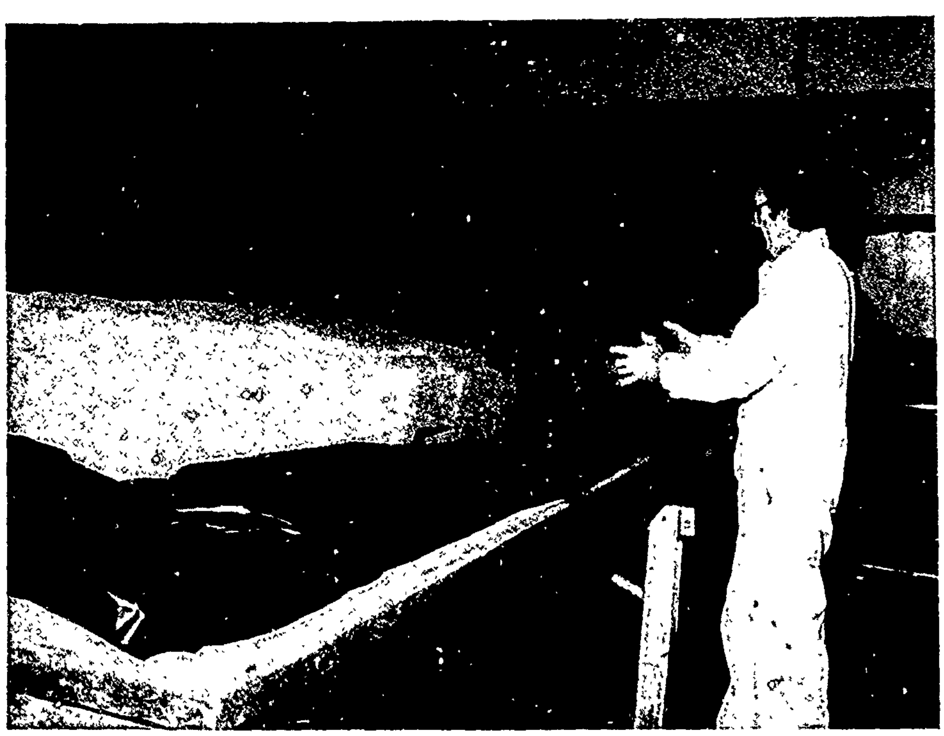

Figure 7. Foam Preparation

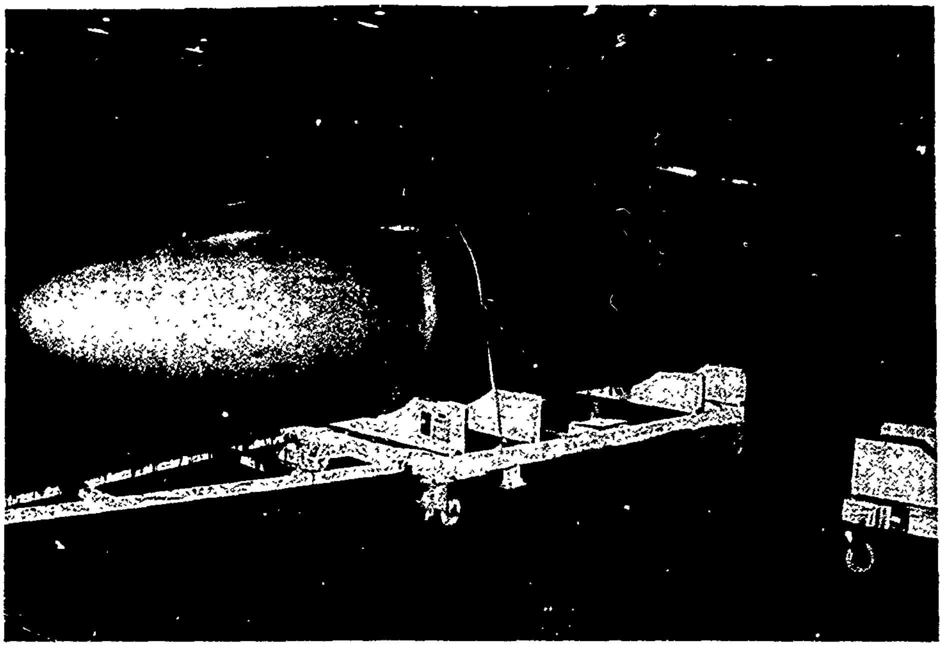

Figure 8. External Fuel Tank

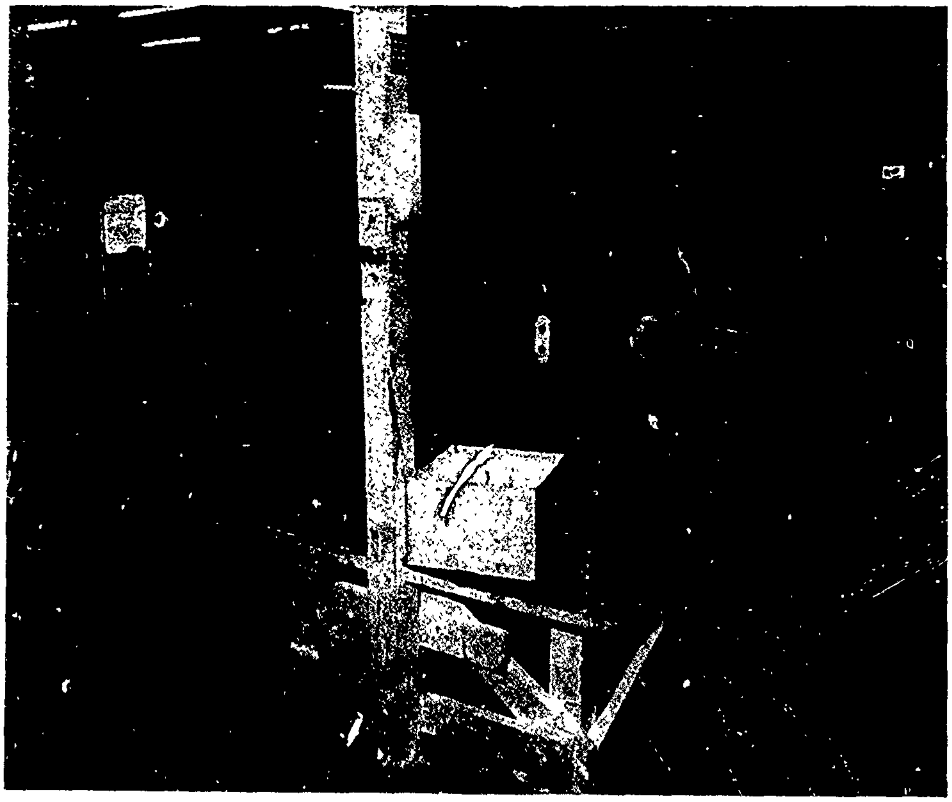

Figure 9. Center Wing Bladder Cell

NEW MATERIAL DEVELOPMENTS

Another problem with the foam has been experienced. Within months after the blue foam-equipped C-130 started operations in the field, some 10 electrostatic incidents occurred. Following the first incident, a "fix" to increase the void in the foam adjacent to and under the fuel level control valve (FLCV) and the filler caps was planned. The void would extend to the bottom of the tank. This was planned to reduce the fuel impingement into the foam during the refueling operation, thus reducing the electrostatic generation and potential hazard.

Before this foam fix could be incorporated, other incidents occurred or were discovered. It was decided that fuel impingement onto the foam must be eliminated during fueling. An accelerated effort by WR-ALC engineering was undertaken to design a shroud for installation around each FLCV, extending to the tank bottom. A similar device would be installed around each filler cap, also extending to the bottom of the tank.

The prototype shrouds were installed and checked for fuel system compatibility by WR-ALC. Tests to ensure that the shroud has no adverse effect on the FLCV and its operation were conducted by the Aero Propulsion Laboratory (APL) at Wright-Patterson Air Force Base, Ohio. Tests in the APL Electrostatic Flow facility explored the comparative electrostatic activity between a shrouded C-130 FLCV and a non-shrouded valve over a range of flow rates and fuel conductivity levels. The tests proved that reducing the fuel impingement into the foam did lower the electrostatic activity. These tests also suggested that this electrostatic change could be reduced further by using a polyester foam baffle between the fuel entry point and the blue foam. Thus, the current blue foam configuration of shrouds and Type II, yellow foam inserts (installed at the fuel entry points for each tank) evolved. This concept was proven in tests in the climatic hangar at Eglin AFB, Florida, and became the baseline foam installation for the USAF C-130 force in the fall of 1983.

Figures 10 through 14 depict the shrouds and blue/yellow foam for installation around the FLCV and filler cap.

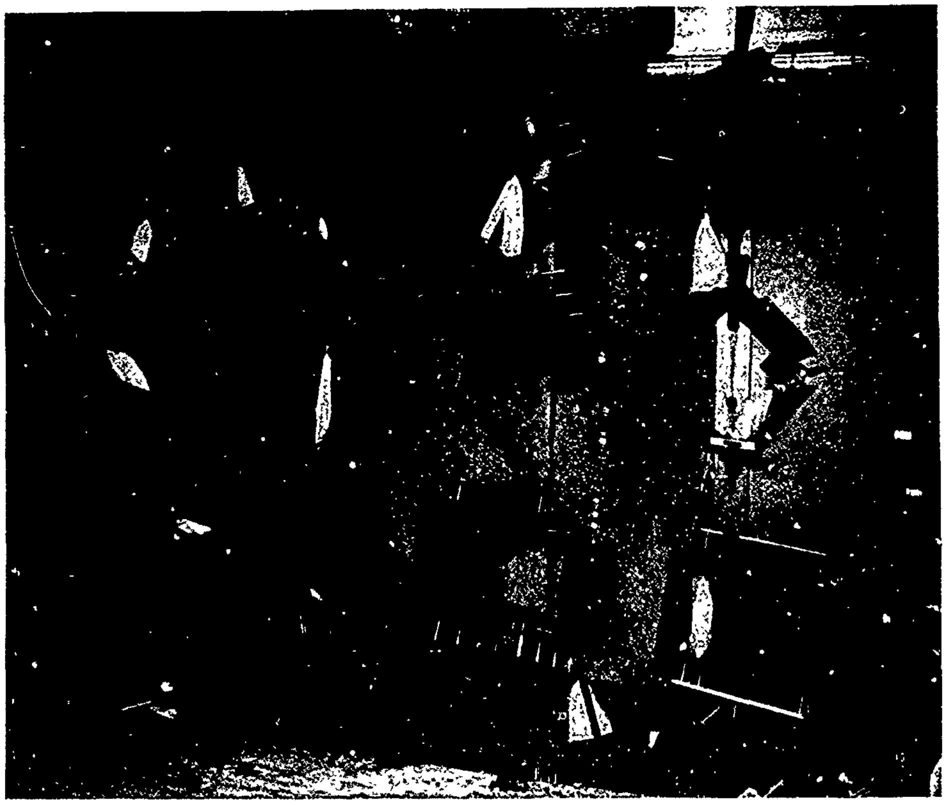

Figure 10. Shrouds

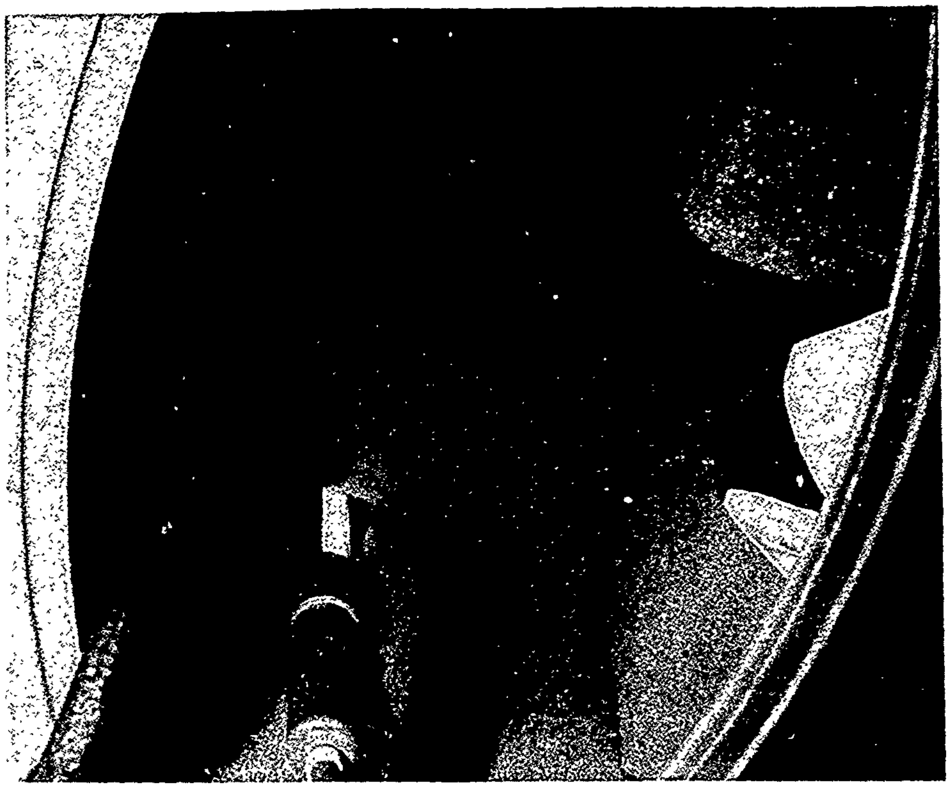

Figure 11. Blue and Yellow Foam

Figure 12. Blue and Yellow Foam

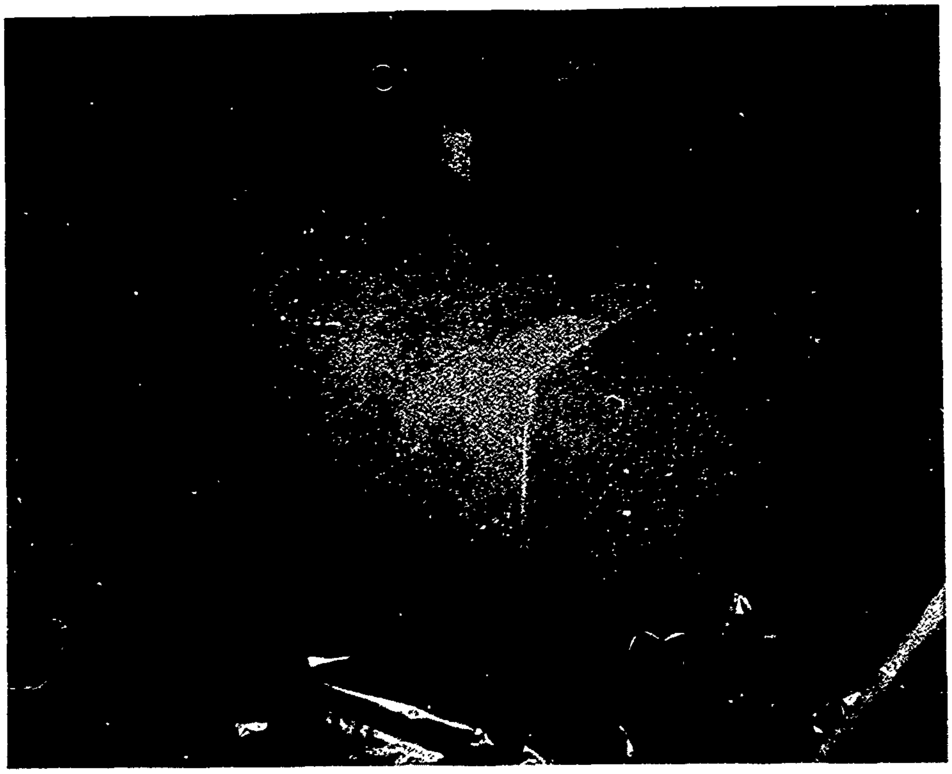

Figure 13. Blue and Yellow Foam

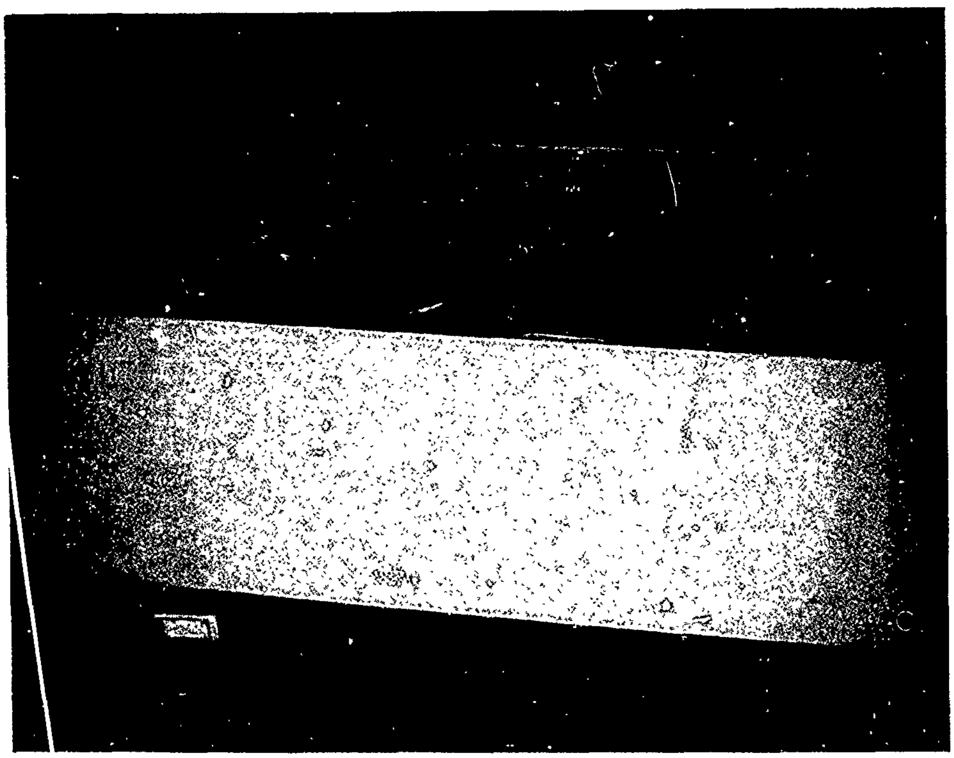

Figure 14. Foam Shipment

While the above modification seemed to solve the refueling incidents, evidence of electrostatic-caused fire in the fuel tanks continued to be reported. Since these incidents appeared to follow high-energy aircraft maneuvers that may have produced rapid fuel movement through the foam, the conclusion was that a new foam material with high electrostatic conductive characteristics needed to be developed. This task was undertaken by the Aeronautical Systems Division (ASD) at Wright-Patterson AFB. The design goal for electrical resistance of 5 x 10^{12} ohm-cm was established. (The Type IV and V blue foams exhibit about 10^{15} ohm-cm). Several foam candidates were offered and, following lab tests by ASD, were extensively flight tested by the Air Force in the A-10.

The A-10 results were very encouraging, leading to service evaluation testing of a couple of the foam candidates presently in the C-130. The interim results are good, and future C-130 foam installation probably will be fabricated from the new conductive foam materials.

The early conductive foams are produced by a post process performed on the basic polyether foam to incorporate desired electrostatic features. The latest candidate foam product is formulated with inherent or "in-situ" conduction characteristics. Both foam types are allowed by the Air Force foam technical document, TE-ENFE-86-1 (11 Feb 87), "General Exhibit for Electrically Conductive Explosion Suppression Material." Allowable porosity and density levels are shown below:

Type	Color	Density (Lbs/Ft3)	Porosity (PPI)
VI	*	1.2 - 1.55**	8 - 18
VII	*	1.2 - 1.55**	24 - 34

* Color may not be blue, orange, yellow, or red

** Exact values to be set by procuring activity

The fabrication and installation times of these conductive foams are similar to those of the blue foam configuration. The foam density, the fuel displacement, and the fuel retention characteristics are similar between the conductive and the blue foams, as noted in the table. Of course, the fire suppression capabilities should be identical.

C-130 WING IMPROVEMENTS

Coincident with the evolutionary development of explosion suppressant foam material was an evolution in C-130 wing design. In 1982 a new outer wing design was developed that greatly enhances the maintainability features, improves corrosion resistance, greatly increases fuel tank sealing integrity, and improves overall durability. Up to this point, fuel tanks with foam installed incurred fuel system maintenance penalties, foam deterioration, electrostatic discharge-induced flash fires, field level availability of replacement foam, and foam handling problems. In addition to measures taken to alleviate foam problems, one feature is of singular significance in reducing maintenance costs and aircraft downtime with increased fuel system serviceability. A total of 40 internally mounted fuel probes have been replaced by 22 externally mounted fuel probes.

Maintenance and repair of the fuel quantity gauging system in the past has required that the airplane be isolated, electrical power removed, and fuel tanks opened, drained, and purged. The new design permits troubleshooting and/or replacement of fuel probes without tank entry, and with fuel in the tanks. These new fuel-measuring probes are installed or removed through an access hole in the upper surface of the wing. The lower end of the probe is secured in a rubber grommet mounted on a bracket attached to the lower skin panel, while a flange at the upper end of the probe mates flush with the wing surface to provide a fuel-tight seal.

The combination of a reduced number of fuel probes, together with the simplified wiring hookup, greatly enhances troubleshooting and replacement procedures. The results are a significant reduction in fuel system maintenance man-hours per flight hour.

Figures 15 through 18 illustrate the installation of the externally mounted fuel quantity probes.

Improvements were also made in other design details particularly with respect to sealing enhancements. The C-130 sealing system uses corrosion-inhibiting polysulfide sealant in all faying surfaces during assembly. With air pressure the tanks are then inspected. Most fasteners are Hi-Tigue interference fit pins with seal nuts. Fasteners are installed wet with corrosion-inhibiting sealant, and all fasteners penetrating the fuel tank boundaries are double brush overcoated with MIL-S-8802 sealant. Post assembly sealing consists of applying fillets to all seams and joints. Further, all tank interior post assembly sealant is overcoated with a flexible polyurethane coating to prevent sealant degradation from mercaptans contained in jet fuel. As a final check on fuel tank sealing integrity, a high level fuel soak is performed using a standpipe to augment the pressure.

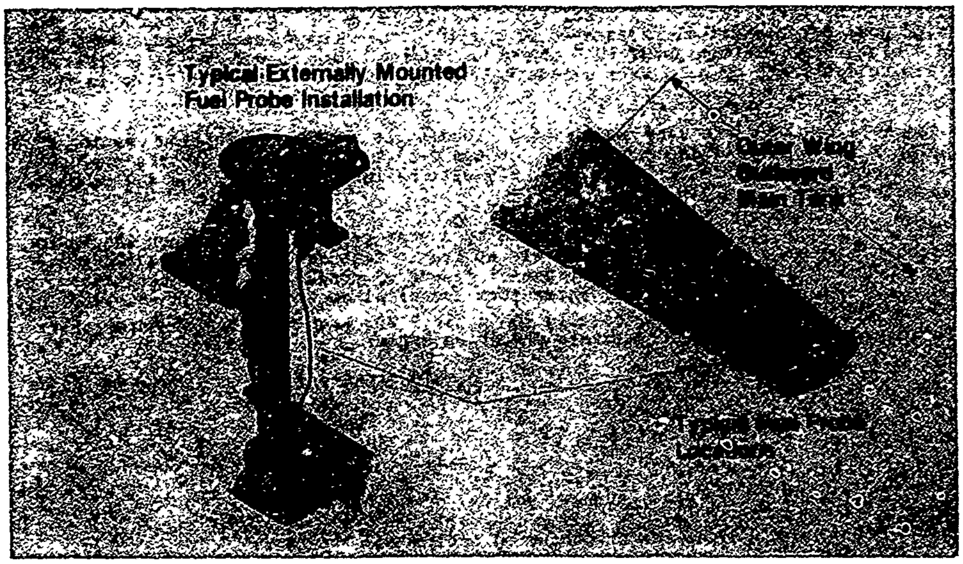

Figure 15. Probe Installation

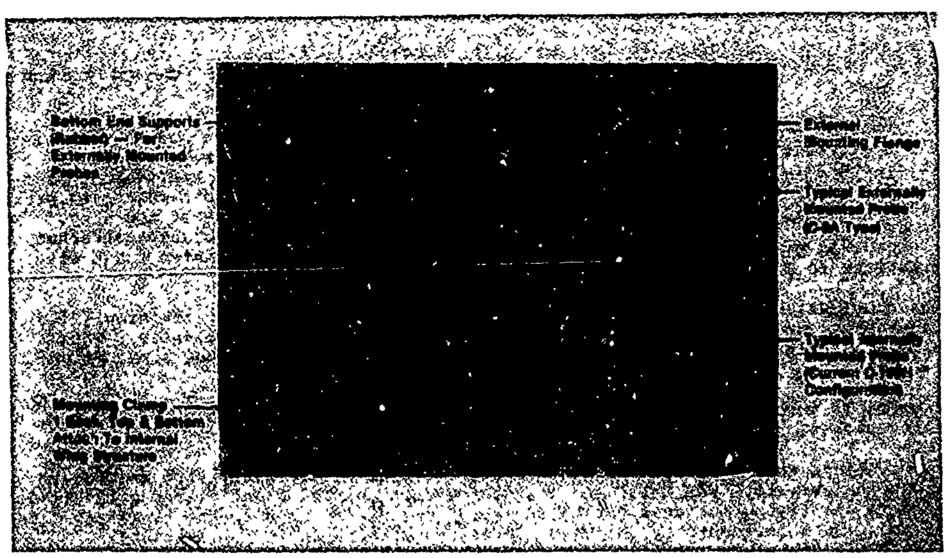

Figure 16. Probe Detail Components

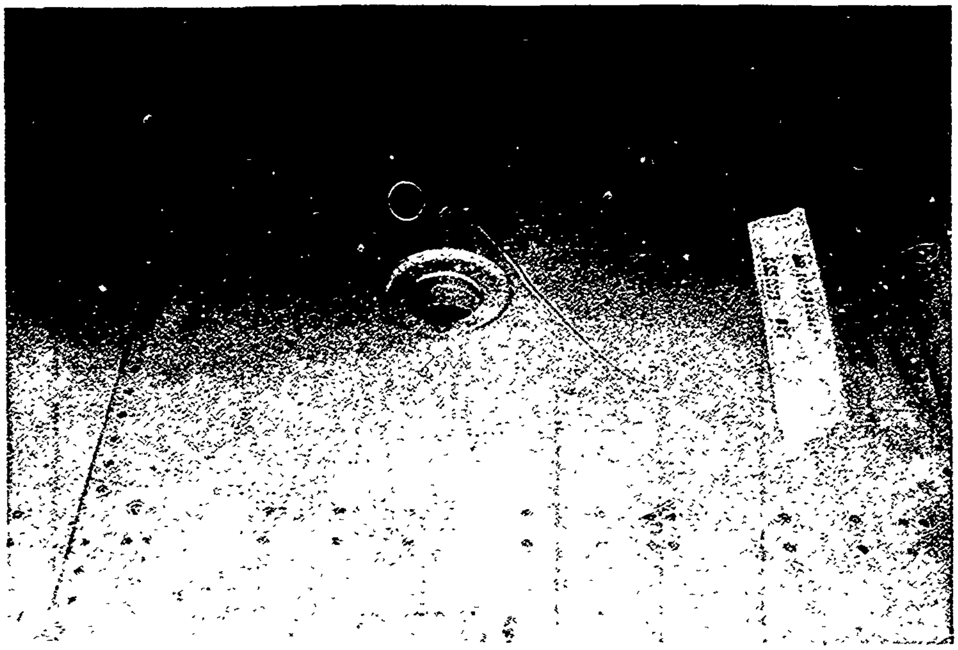

Figure 17. Exterior Wing Surface Probe Mounting

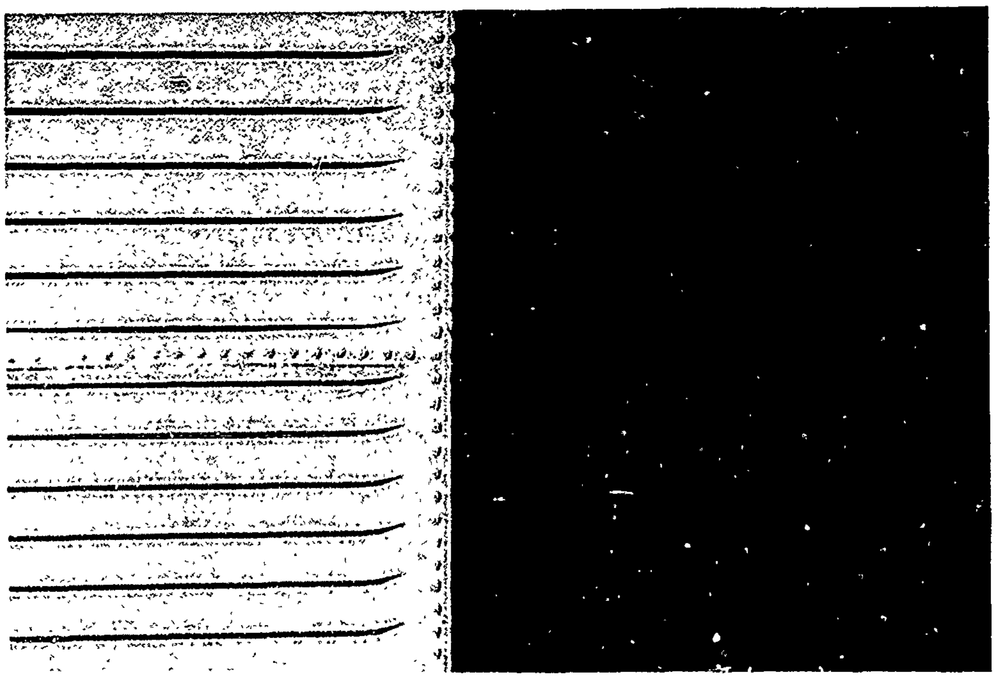

Figure 18. Interior Surface

Sealing system improvements have resulted in a drastic reduction in maintenance man-hours per flight-hour due to fuel leaks. The relative reduction in maintenance man-hours per flight-hour with sealing improvements over successive changes is shown in Table 1.

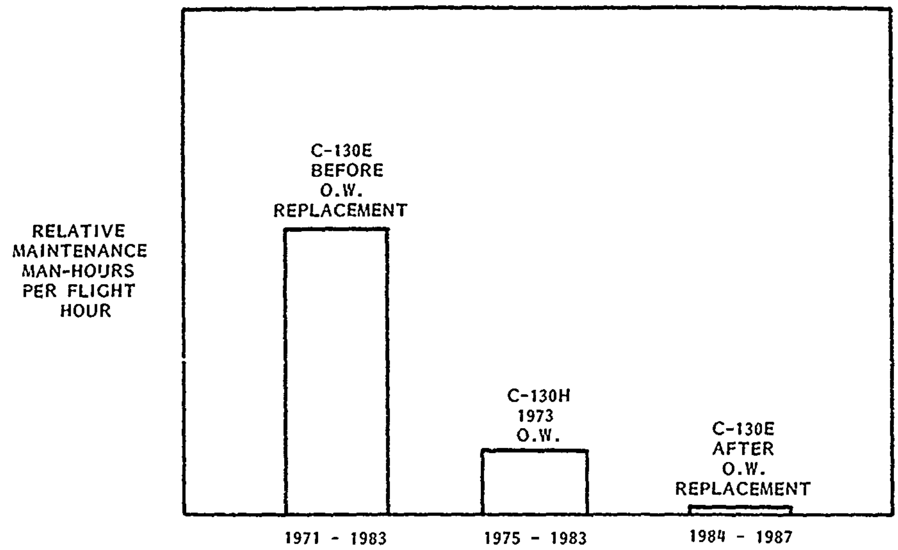

TABLE 1. IMPROVED TANK SEALING

The combination of externally mounted fuel probes, improved sealing and finish systems, more corrosion-resistant materials, selective structural beef-ups, and a host of other changes results in wing fuel tanks that require minimal maintenance and tank entry. This favorable fuel tank maintenance trend bears directly upon the performance of reticulated foam as a cost-effective fuel tank explosion suppressant.

ALTERNATE FIRE EXPLOSION SYSTEMS

As an alternative to reticulated foam, a fire protection method that suppresses fire, an active fuel tank inerting system seeks to eliminate the ullage oxygen leg of the fuel-oxygen-ignition source fire triangle. Nitrogen systems dilute the oxygen concentration in the ullage to levels below that required for combustion.

It is not enough for an inerting system to prevent or dilute the entry of atmospheric air. The system must also control the entry of air that has been dissolved in the fuel. Aircraft fuel is stored where it is exposed to the atmosphere and is, therefore, normally saturated with dissolved air. Moreover, fuel will dissolve oxygen in a higher ratio to nitrogen (about 1 part oxygen to 2 parts nitrogen) than exists in the atmosphere. During climb, the decreasing ambient pressure reduces the amount of dissolved air that can be retained in solution in the fuel. This oxygen-rich gas will evolve and will increase the oxygen concentration in the ullage. The ullage oxygen will increase from 21 percent at sea level to about 35 percent at 40,000 feet. Should the ullage be inert (less than 9 percent oxygen) at sea level, this dissolved oxygen will destroy the inert ullage as it comes out of solution during flight.

Two methods have demonstrated control of this dissolved oxygen. The first uses the inert ullage to scrub the fuel as it is loaded into the aircraft, the "aspiscrub" method. The C-5 now uses aspiscrub to remove the entrained oxygen in the fuel to a level of 5 percent at sea level which, when released during climb, rises to less than 9 percent at altitude. The original C-5 system scrubbed the fuel during climb by using a two-phase fuel-nitrogen jet underneath the fuel surface. This "climb-scrub" system, operated periodically during climb to conserve nitrogen, maintained the ullage oxygen concentration at less than 9 percent at all conditions.

Active systems are generally lighter, cause less unusable fuel and allow easier in-tank inspection and maintenance than the passive methods do. Foam deteriorates with time and clogs the fuel filters. An active inerting system would eliminate this

cause of filter contamination. Foam also requires special handling and wrapping if it is to be out of the tank for an appreciable length of time. Further, used foam which is no longer usable is difficult to dispose of without environmental damage. Active inerting offers only limited multi-hit protection, however, and no fuel-induced hydraulic ram suppression. It also may require periodic servicing of the inerting medium. There is a trade-off in that parts would be required to be maintained in Air Force mobility parts kits. Additionally, inspections and maintenance on an active fuel tank inerting system will be required.

The present active inerting methods available to a C-130 are the liquid nitrogen (LN_2) and the onboard inert gas generation system (OBIGGS). The OBIGGS may have the best supportability potential since the LN_2 requires special ground support, servicing, and logistic capabilities.

Liquid Nitrogen

The liquid nitrogen (LN_2) fuel tank inerting method uses nitrogen to dilute and purge the oxygen from the fuel tank ullage. The nitrogen is carried onboard the aircraft as a liquid in Dewars.

The LN_2 system operates by routing the LN_2 from the Dewar to a heat exchanger that produces gaseous nitrogen (GN_2). The GN_2 is plumbed to a common tank vent box that communicates with all of the fuel tanks. To minimize the nitrogen supply, a climb and dive vent control valve is installed in the vent box. This valve causes the fuel tank to remain inert without crew or ground support as long as there is LN_2 in the Dewar.

The LN_2 system uses the separator aspiscrub fuel scrub method similar to that used on the C-5. The aspiscrub system uses ejector action of the onloading fuel to mix the nitrogen in the tank ullage with the fuel, thus releasing any dissolved oxygen in a controlled manner and dumping this oxygen-rich gas overboard as the tanks are filled.

Liquid nitrogen is an effective inerting medium and has been shown to be a lightweight, cost-effective method for large aircraft operated from a fixed base. Since aircraft designs using LN_2 inerting prevent air from entering tanks by maintaining the tank pressure above outside ambient, the fuel tanks remain free of dirt, dust, and water vapor.

A major disadvantage of LN_2 is the logistics of providing LN_2 and servicing equipment prior to each flight. Also the LN_2 inerting system needs cryogenic plumbing and storage equipment, which are expensive and virtually nonexistent in the majority of C-130 operational bases. For this reason, LN_2 inerting has not been seriously considered for replacement of reticulated foam in the C-130 fleet.

Onboard Inert Gas Generator System (OBIGGS)

Two OBIGGS concepts were investigated under the sponsorship of Air Force Wright Aeronautical Laboratories. These are the molecular sieve inert gas generator (MSIGG) reference 1, and the permeable membrane inert gas generator (PMIGG) reference 2, systems. Both concepts produce nitrogen enriched air (NEA) to dilute the oxygen in the fuel tank ullage to concentration levels that will not support combustion (O_2 9 percent).

The climb-scrub technique will be used by either OBIGGS to scrub and control the releasable oxygen-rich gas from the fuel during climb operations. This subsystem, which is tied into the tank pumps, will operate continuously during climb.

A schematic of a typical OBIGGS installation concept considered in this study is shown in Figure 19. Storage of NEA is needed for rapid descent modes and for system redundancy. Conditioned air flows through the air separation module (ASM) with the resulting NEA flowing either to the compressor/storage or directly into the fuel tanks or a combination of both. Both concepts have been considered for the C-130 aircraft as a possible inerting or fire protection method.

Molecular Sieve (MS) OBIGGS

The molecular sieve (MS) concept of air separation is based on pressure swing cycle adsorption of oxygen using a zeolite molecular sieve material arranged in a pair of identical beds. Zeolite is a synthetic crystalline material that has the special property that adsorbs oxygen molecules to the exclusion of nitrogen molecules.

The pressure swing cycle adsorption technique uses pressure to control the adsorption/desorption process. High-pressure air is fed into the entrance of the bed. As this air moves through the bed, much of the oxygen enters the zeolite crystals and is adsorbed. This results in a stream of nitrogen-enriched air for fuel tank inerting. Before the bed becomes saturated with oxygen, the pressure is cycled back to ambient, and the oxygen is desorbed and flushed out of the bed.

By combining beds in pairs that are pressurized and flushed on a regular cycle, a continuous flow of oxygen-depleted product is produced with sufficient pressure and waste flow for the flushing operation. Several pairs of beds can be linked to produce

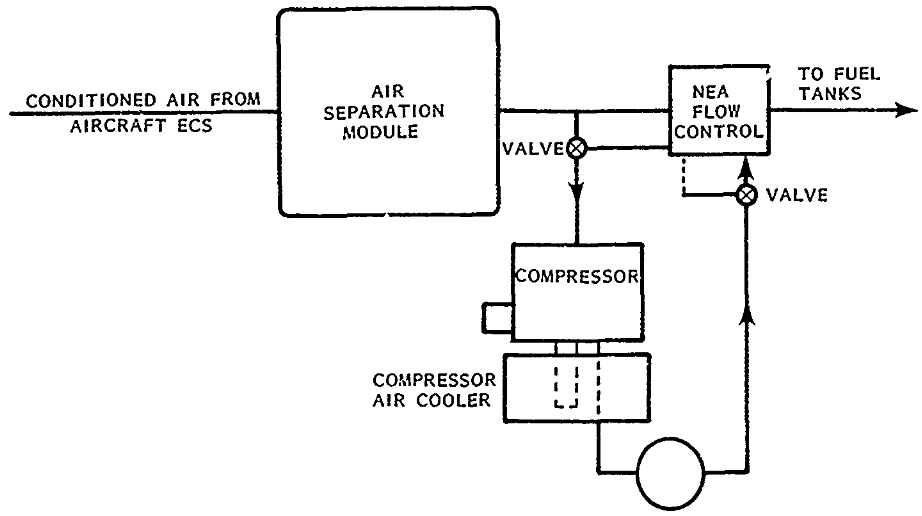

Figure 19. OBIGGS Inerting Concept

the desired product flow rate. This separation concept is to be used for the OBIGGS installation for both the USAF C-17 and the Army/Navy V-22 transports.

Permeable Membrane OBIGGS

The permeable membrane (PM) air separation technique uses a membrane material that exhibits preferential gas mass transfer properties. Gas transfer through the membrane occurs in three steps. First, the preferential gas (oxygen) dissolves into the polymer surface, next the oxygen concentration gradient induces diffusion through the polymer wall, and finally oxygen evolves out of the opposite surface of the membrane. Water vapor also permeates through the membrane along with the oxygen, resulting in a nitrogen-enriched air (NEA) stream free of water. The quality and quantity of gas transfer varies directly with surface area and inversely with membrane thickness.

Since the permeability of these materials is quite low, large surface sheets of very thin membranes are required to produce large quantities of inert gas. By producing fiber membranes and preparing them in cylinders, practical air separation modules (ASM) are possible.

It is projected that new, second generation PM ASMs will produce NEA flow and quality at about one-fourth the size and weight of the current PM ASMs units.

FUTURE ADAPTATIONS TO C-130 AIRCRAFT

Studies of potential OBIGGS for a C-130 in lieu of the foam installation have been made by Lockheed and others (reference 2). The latest C-130 configuration, which would use the second generation PM IGG separation technique, could be installed in a C-130 with a weight penalty of 1200 pounds compared with the weight penalty of 2949 pounds for a blue foam installation. Cost comparisons show that foam is cheaper to procure and install in a C-130 than OBIGGS. However, when the additional maintenance time and man-hours are included, the OBIGGS offers potential life-cycle-cost savings that could justify OBIGGS installation from a maintenance standpoint alone. When additional OBIGGS operational experience is obtained from the V-22 and the C-17 programs, the validity of any maintenance estimates for the C-130 OBIGGS can be assessed. Recognizing the weight savings of the OBIGGS will improve the relative cost picture between the two fire protection methods even more for the C-130 application. Table 2 presents the C-130 system weight and usable fuel comparisons.

CONCLUSIONS

1. Fuel tank explosion suppressant foam is an effective means of preventing fuel system explosions induced by gunfire, uncontained engine failure damage, lightning and electrical sources.

2. C-130 experience with safety foam has been excellent in terms of protection afforded.

3. Electrostatic discharge problems with the blue foam are being addressed by using shrouds and yellow foam inserts around fuel fillers. The new conductive foams offer potential to eliminate the electrostatic problem entirely.

SYSTEM WEIGHT AND USABLE FUEL COMPARISONS

METHOD	SYSTEM WEIGHT	AIRCRAFT USABLE FUEL
RETICULATED FOAM	2949 LBS	BASELINE
LIQUID NITROGEN	1550	+1400 LBS
MOLECULAR SIEVE OBIGGS	1500	+1350
PERMEABLE MEMBRANE OBIGGS	1200	-1350

TABLE 2. C-130 FUEL TANK EXPLOSION PROTECTION METHODS

4. The new C-130 outer wing configuration with externally mounted fuel quantity probes has greatly reduced maintenance costs associated with foam removal and fuel quantity probe replacement.

5. Other design and sealing improvements on the new C-130 outer wing have contributed to the reduced need to enter the fuel tanks with resulting maintenance activity decrease.

6. Alternative means of protecting fuel tanks from explosion through inerting methods would appear to become increasingly more competitive with foam protection.

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2. Johnson, R.L. and J.B. Gillerman, AiResearch Manufacturing Company, prepared for Aero Propulsion Laboratory, "Aircraft Fuel Tank Inerting Subsystem," AF-WAL-TR-82-2115, July 1983.

ACKNOWLEDGEMENTS

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A DYNAMICIST'S VIEW OF FUEL TANK SKIN DURABILITY

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SUMMARY

Widespread leakage of fuel tanks in military aircraft is believed to be aggravated by small cracks induced by premature fatigue of skins from fluid- structure interaction loading and dynamics. A developing method is shown that will help improve designs to avoid this recently recognized problem. The technique treats flat panels, curved panels, and stiffened panels. Parallel panels configured as sides or top and bottom pairs are included. Panels of a representative fuel tank section of typical aircraft construction were analyzed, tested, and are included. This method has been under steady and careful development for a number of years so that high confidence would be established at each step. A well balanced analytical and experimental approach was taken. It is now mature and ready for full scale application.

NOMENCLATURE

l	-	frequency in radians per second
ϕ	-	mode shape
ε	-	strain
μ	-	microstrain
AFWAL	-	Air Force Wright Aeronautical Labs
BCM	-	Boundary Condition Method
BEIGER	-	Fatigue Code
CADD	-	Computer Aided Design and Drafting
CAST	-	Computer Aided Structural Technology
CGSA	-	Computer Graphics for Structural Analysis
CM	-	Continuity Method
CYRUS	-	Fatigue Code
f	-	frequency in Hz
Hz	-	Hertz, cycles per second
IRAD	-	Independent Research and Development
M	-	Mass
MCAIR	-	McDonnell Aircraft
N	-	cycles
NASTRAN	-	NASA Structural Analysis Routine
NSFACE	-	NASTRAN Interface Routine
PSD	-	Power Spectral Density
r	-	radius of curvature
rms	-	root mean square
USAF	-	United States Air Force

INTRODUCTION AND BACKGROUND

Two research programs were sponsored by the USAF to develop techniques to avoid premature fatigue induced by fluid-structure interaction. They were preceded by independent research at McDonnell Aircraft Company (MCAIR), and effort at MCAIR has continued since then.

The Independent Research and Development (IRAD) at MCAIR began in 1975 in an effort to explain two incidents in 1974-1975 where structural damages had been traced to fluid-structure interaction mechanisms. In the first case, a fuel tank skin was cracked in a nominal slosh and vibration test. The crack was initiated because of an overstress condition resulting from coincidence of the slosh frequency and the panel skin resonance that was lowered due to fluid mass coupling. The dry tank showed no evidence of these large strain amplifications and thus did not crack. In the second case, a wing skin was cracked in nominal high speed flight. This was traced to a panel flutter which appeared to be induced only when fluid-structure interaction was present. Both problems were cured by structural beef-up.

In view of these incidents, a general investigation into the underlying process was started in 1975. It was believed necessary to develop a comprehension of the fluid dynamics and how they varied in several applications. A number of methods were investigated regarding ways of representing the fluid motions. These included momentum methods, field potential methods, and fluid velocity profile methods. The latter was used more extensively because of its versatility and accuracy.

Three applications were used initially to assess this newly recognized phenomenon: (a) fuel tank skin fatigue, (b) panel flutter of fuel tank skins, and (c) hydraulic ram, as captioned in Figure 1. Our initial findings were dramatic. Significant effects of fluid-structure interactions were seen in all three cases. In fuel tank skin fatigue, we found a potential new fatigue source and perhaps an explanation of leakage. In panel flutter, it was shown that the added interaction of fluid-structure could lower flutter boundary speeds in general. In hydraulic ram, it was shown that the fluid-structure interaction produced extremely large pressures on the skins compared to the dry state. Though this approach differed from earlier investigations, it supported the thesis of the transfer of large amounts of energy to the fluid then to the skins during ballistic impact. Results of this effort were summarized in Reference 1.

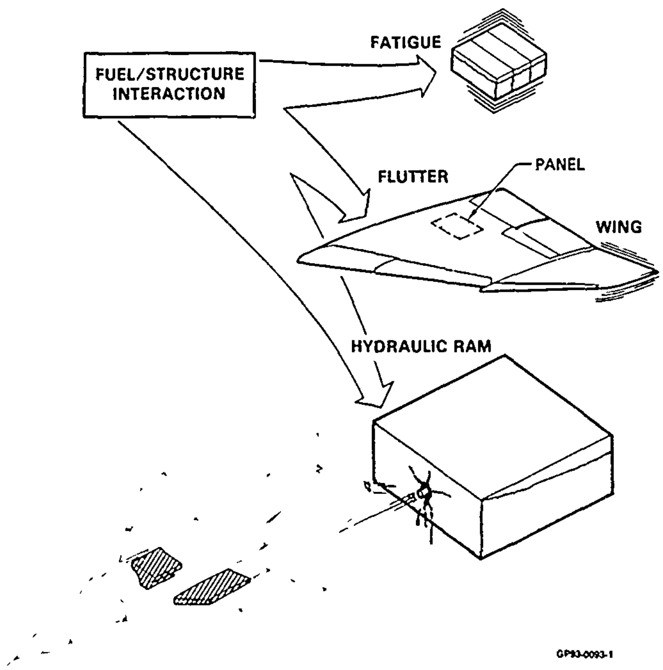


Figure 1. Applications of Fuel/Structure Interaction

The USAF meanwhile was pursuing methods to stem leakage and fatigue incidences. Considerable efforts were made in general design approaches, sealing techniques, leak detection methods, and qualification testing that included environmental effects and maneuver load spectrum fatigue. Considerable progress was made in these areas.

In late 1977, contact was made with AFWAL, WPAFB, to discuss the MCAIR findings on the fatigue potential due to fluid-structure interaction. Of the three mechanisms explored, fatigue, flutter and hydraulic ram, we at MCAIR believed that fatigue was probably the most important area to pursue at that time. Immediate interest was triggered because of the widespread reports of leakage, and because USAF had experienced fatigue not accurately predicted by nominal maneuver load spectrum, see Reference 2 for example. Recognizing that a potential explanation of aircraft fuel tank fatigue and leakage problems was possible, AFWAL encouraged the MCAIR work on fatigue. AFWAL released an RFP in 1979 which resulted in MCAIR's winning the first research contract, Reference 3 spanning the period 1981-1982. Here the formative McDonnell work was blossomed into an accurate method for predicting flat bottom panel as response and fatigue reported in Reference 4. A second AFWAL contract win by MCAIR was conducted over the period 1984-1987, Reference 5. This second research contract extended the earlier research into a formidable technique for more complex cases. Studies were made on side panels, parallel sides, parallel top/bottom pairs, curved and stiffened panels, and panels of a representative tank section of typical aircraft construction. This effort was divided into six tasks, I-VI as shown in Figure 2. The first contract employed mostly sine excitation in order to start fundamentally. The second used many cases of more complex loading such as random excitation, and many cases of combined vibration and low frequency maneuver load spectrum. The results of the second research are thoroughly summarized in Reference 6.

This paper will highlight our most recent studies to show how far the method has progressed technically and the broad applications made. Related papers in References 7 to 10 give added details.

Task I
- Flat Panels
  - Multimode Sine and Random
  - Parallel Walls, Sides, Top/Bottom

Task II
- Curved Panels
  - Bottom, Sides
  - Parallel
  - Single, Multimode

Task III
- Stiffened Panels
  - Bottom, Sides
  - Parallel
  - Single Multimode

Task IV
- Nonlinear Effects
  - Membrane Influence
  - Large Deflection

Task V
- Sealants Bladders, Foams

Task VI
- Stylized Tank

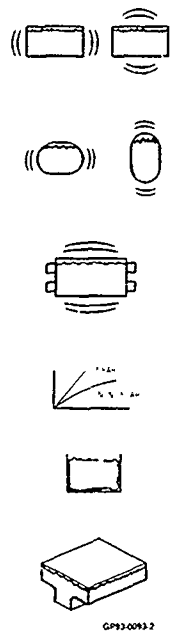


Figure 2. Task Descriptions

ANALYTICS

o Basic Concepts

The underlying process which produces these recently recognized and dramatic influences in fuel tank skin fatigue is the coupling of fluid and structural motions. This is not slosh, but rather a higher frequency process which produces large strains in skins due to nominal aircraft vibration environment. Oscillations of the skins produce oscillations of the fuel which then couples with the skin vibration, creating a modified vibration. This is much like a feedback concept as shown in Figure 3. The added fluid mass produces lower frequencies, thus moving panels toward regions of higher levels of excitation. Likewise, the mass effect of the fluid column produces larger strains than the dry state, thus increasing the fatigue potential further. This is portrayed in Figure 4 where the dry versus wet skin response is shown to be greatly different. The dry case is not critical, while the wet case is. This is further complicated in terms of fatigue as shown later.

The analytics of the fluid dynamics and the coupling of the oscillations with the skin are quite complex. These are detailed in References 4, 6, 8, and 9. It was found that the fluid oscillation coupling was basically a mass effect because of the incompressible fluid dynamics that resulted. Slosh effects were not included because they were thought to be of lesser significance, but they could be readily incorporated. The fluid dynamics were based on velocity profile concepts which satisfied Laplace's Equation for physics and also matched the motions at vibrating panels and at stationary and rigid walls.

Figure 5 shows the analytical process available as a fully automated comprehensive code. There are three parts to the code as shown in the flow chart. The first part is the vibration module which couples the fluid dynamics to the panel dynamics to produce the merged dynamics needed. The second part is the strain response module where panel amplitudes and strain are found for various excitations; sine, narrowband random, and broadband random. These are moving base excitations for the appropriate analogy to environmental vibrations. The third part is the fatigue code which establishes fatigue life for a given situation for the data from the first two parts of the code. We have made improvements to the code in both contracts, with major expansions made to all three parts in the latest effort.

o <u>Vibration</u>

The vibration module was expanded under the latest contract, Reference 6, to include parallel panels, slightly curved panels, and to interface with NASTRAN so that panels of a general structure could be handled. Figure 6 is a flow chart of the current version. Dry panel vibration for flat or curved panels, individual or parallel, is merged with the fluidic effects to produce coupled vibration. Dry panel vibration data from NASTRAN is treated in the same fashion.

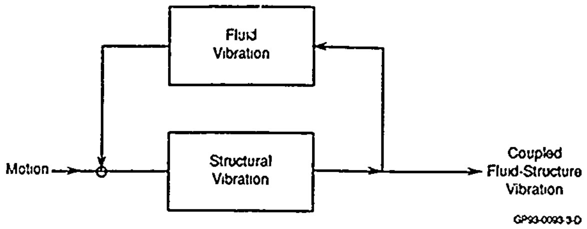


Figure 3. Schematic of Fluid-Structure Interaction and Vibration

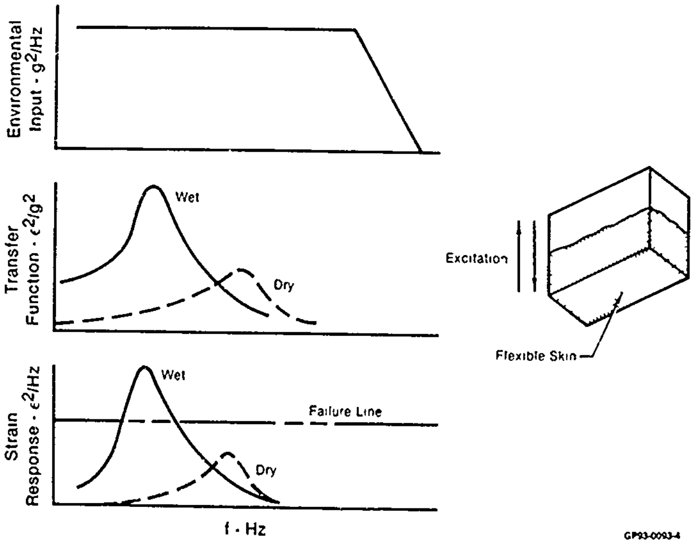


Figure 4. Wet vs Dry Response

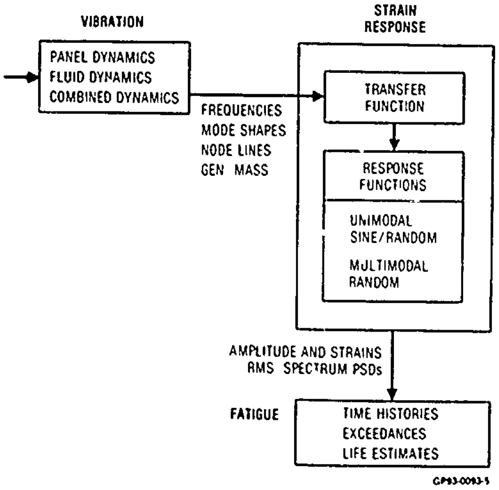


Figure 5. Fuel Tank Durability Code Flow Chart

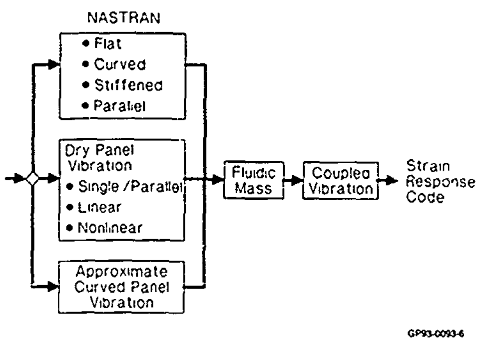


Figure 6 Flow Chart of Expanded Vibration Code

The parallel panel solution is illustrated in Figure 7. The substructure solution method of Reference 11 was used. Each side is vibrated independently to couple the fluidic effects, then both sides are completely coupled. The cross coupling of both sides is accomplished by a through-the-fluid effect which we believe to be unique to this work. It was confirmed by lab tests in the AFWAL work and the earlier MCAIR work. This solution also produces exactly our single panel solution of the first AFWAL contract. A closed form Raleigh type solution for the panel dynamics and fluid coupling was employed, Reference 6. A slightly curved panel solution based on closed form solutions of Reference 12 was incorporated.

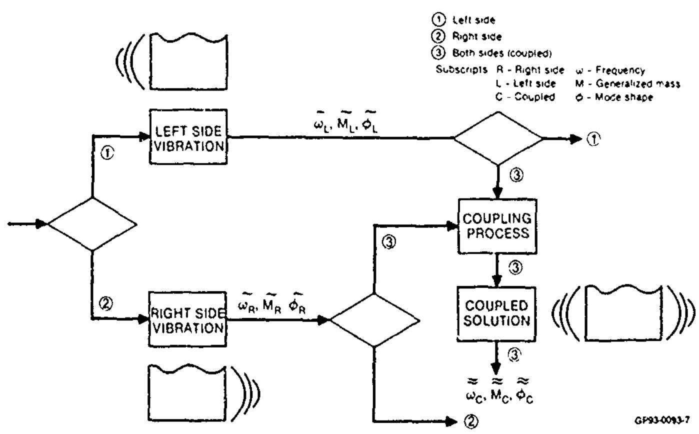


Figure 7. Vibration Solution for Parallel Flexible Walls Using Substructure Method

An interface with NASTRAN was developed so that highly curved panels, stiffened panels, or a complete structure could be analyzed and these vibration results could be merged into the overall program. Figure 8 indicates the NASTRAN details. NASTRAN modelling can be done manually or it can be achieved with automated graphics such as used at MCAIR employing the CADD, CGSA, and CAST routines. Once the vibration solution is made, the frequencies, mode shapes and generalized masses are then passed to the interface routine NSFACE, adapted from another Air Force contract, Reference 11. Here data is sorted and passed to our code, where the coupled fluid-structure interaction vibration calculation is accomplished. Then the process goes to the response and fatigue modules. Strategic modifications were made to our basic code to capture the more general NASTRAN data using curve fitting and adapting the results to fit the original process.

o <u>Response</u>

The strain response module computes amplitudes and strains for a single panel or parallel panels. The panels may be flat, curved, stiffened, or part of a complete structure from NASTRAN. Closed forms are used for the simple cases of sine, narrowband random, and white noise broadband random. For general random input numerical methods are used. In the latest effort, two major new improvements were made. A new approach to multi-mode response was made, where the overall case is approximated by superimposing a series of unimodal responses. The other improvement is an expansion of the complete multi-mode case using a new concept to minimize calculations. Correspondingly, computations for rms values were better than our earlier approaches.

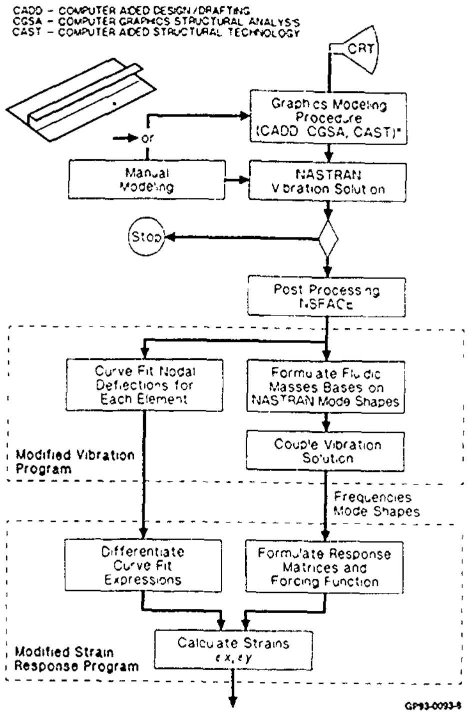


Figure 8. Flow Diagram for NASTRAN Based Fuel Tank Durability Analysis

o <u>Fatigue</u>

Our fatigue method is based on the classic approach of Reference 13 employing the advances of References 14 and 15, with improvements to include newer aspects to cover our extended applications. It is basically a cumulative damage approach, Reference 13, using a cycle by cycle count of damage per Reference 14. A general spectrum approach computation called BEIGER, Reference 15, has been incorporated. It has been extended to the higher frequencies beyond nominal spectrum fatigue and to include combination of static load, maneuver load, and vibratory load stresses. It simulates the random time history from the Power Spectral Density, PSD ,to determine the strain-cycle count needed for fatigue. The second and simpler method CYRUS, developed originally in Reference 4, uses the rms of the PSD and an approximate cycle count for fatigue estimate. In our latest versions, Reference 6, we modified CYRUS to base cycle count on the shape and concentration of PSD areas. This is analogous to the centroid of the PSD with respect to frequency. This is a considerable improvement to the earlier CYRUS method which based cycle count in the averaging of major resonant frequencies in the band of interest.

The fatigue code has built-in equations for ε-N data for typical materials with emphasis on bending data, bending with bending preload, bending with tension preload, tension data, and various combinations of high and low cycle data. These were based on our own tests and data from the literature. The user can include his own ε-N data.

<u>EXPERIMENTS</u>

Experiments have been used throughout this work to guide and corroborate theory. Extensive tests were run on beams to develop ε-N data emphasizing bending as opposed to the literature where frequently bending and tension data are not frequently separated. Likewise, extensive tests were conducted on panels to verify the fluidic interaction, panel dynamics and response, and the fatigue of panels under many conditions. It is not possible to review all that was done. Rather, some commentary on the beam tests and selected results of the panel tests will be given. Lastly, correlation of theory and test will be shown to illustrate application.

o <u>Beam Tests</u>

Cantilever beam tests were conducted in the first contract to acquire bending ε-N curves as influenced by bending preload and superimposed low frequency maneuver loading. This followed earlier MCAIR IRAD work with composite beams where preload was successfully applied. In the second contract and in MCAIR IRAD, pinned-pinned beams and fixed-fixed beams were studied. Here the beams were configured so that axial loads could be imposed. Likewise, varying degrees of tension preload and bending preloads were added in an attempt to more accurately match the panel tests. In particular, the fixed-fixed beams with axial constraints, and with bending and axial preload superimposed, matched our fixed edge panel tests more closed.

o **Panel Tests**

A large number of panels were tested under both contracts. In the first, effort, we concentrated on fla· bottom panels to establish confidence in the most basic case. In the second contract, the effort was extended to cover side panels, parallel sides and top/bottom pairs, curved panels configured singly or in parallel, stiffened panels both flat and curved, and panels on a representative tank section. Bags, sealants and foams were investigated to study their effects on fatigue. Vibration frequencies, mode shapes, and strain response were studied for a wide range of excitation levels, fluid levels, with and without static pressure applied, and with low frequency pressure oscillation included. Fatigue tests were run for a total of 57 panels to give a broad data base.

In these tests three tanks were used. The first configuration, Figure 9, was the original tank, References ·, 8, and 9. It provided a height of 12 inches and an opening 10 x 16 inches. It consisted of 1/2 inch thick aluminum walls and was open at two ends where either a single test panel, or parallel test panels were attached. When a single test panel was used, the opposite side was closed off with a thick plexiglass door used for viewing fluidic behavior. All these test panels were secured by sturdy picture frames and multiple fasteners to simulate fixed edges. Panel thickness of 0.032, 0.040 and 0.063 inches were used. This tank was used in Tasks I, II, III, and V. It was subjected to both vertical and lateral excitation, Figure 10.

The second configuration, Figure 11, consisted of a longer or deeper tank derived by adding an extension which was an exact replicate to the first tank. It provided a new depth (or length) of 24 inches, keeping the opening 10 by 16 inches. This was used mainly in Task IV to study nonlinear effects. Sturdy legs were attached to the tanks so that moving base excitation could be applied.

The third configuration was a representation tank section, Figure 12. It was roughly 3 x 3 x 2 feet in size and consisted of a flat bottom, curved sides, and bulkhead type ends. The upper portion was a box beam designed to close off the tank and to allow for attachment of the support legs and a closure (or top) section. Typical aircraft frames, longerons, and stiffeners were used, as were typical sealants and sealing methods. The curved sides and the bottom were divided into 9 bays by the various stiffeners and frames. These bays were designed so that the center section replicated the individual panels of size 10 x 16 inches tested on the smaller tanks, Figure 13. Likewise, the center bottom flat panel was designed to be slightly more critical than the center bays of the two curved sides. The tank was attached to a large electrodynamic shaker via sturdy feet and mechanical fasteners. Moving base excitation was used to drive the tank.

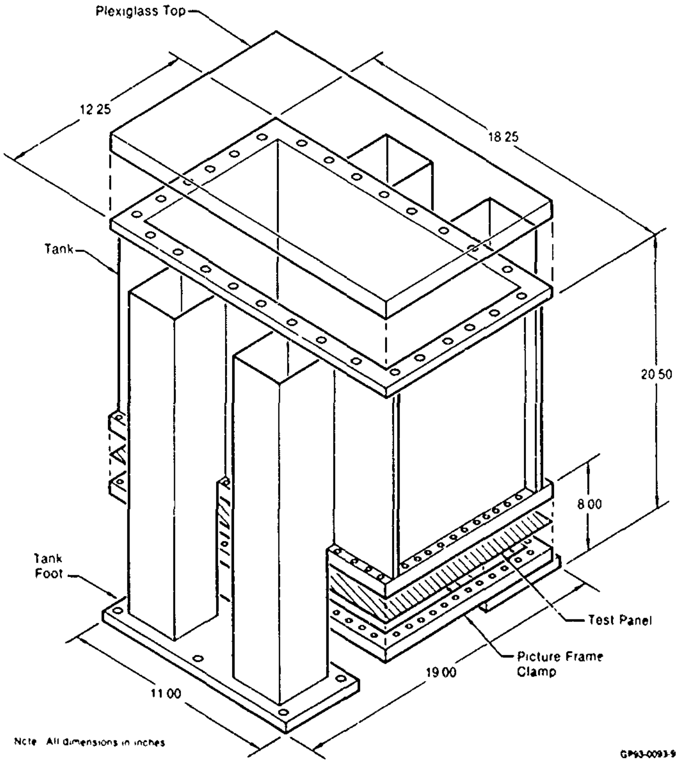


Figure 9. Test Tank for Panel Fatigue Tests
Tasks I – IV

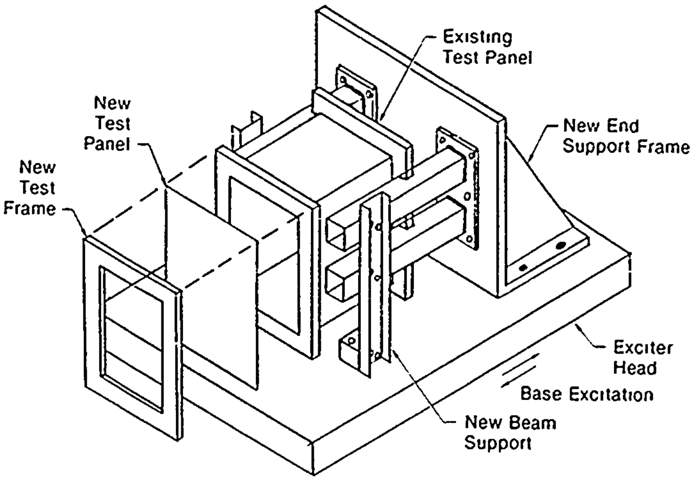


Figure 10 Test Tank Modifications for Side Panel Configurations

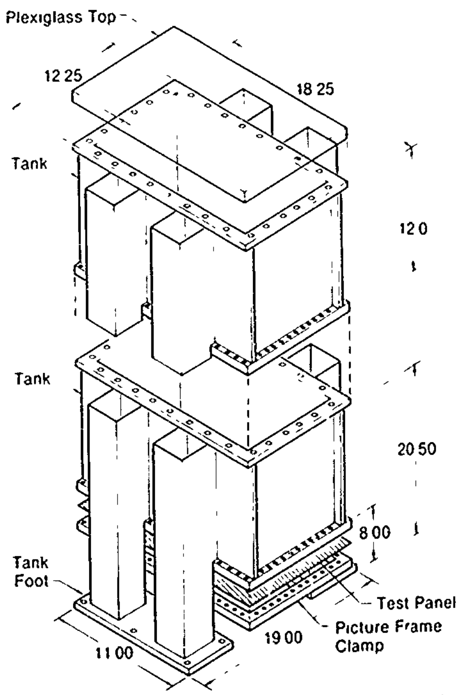


Figure 11. Test Tank Modifications for Tasks III and IV

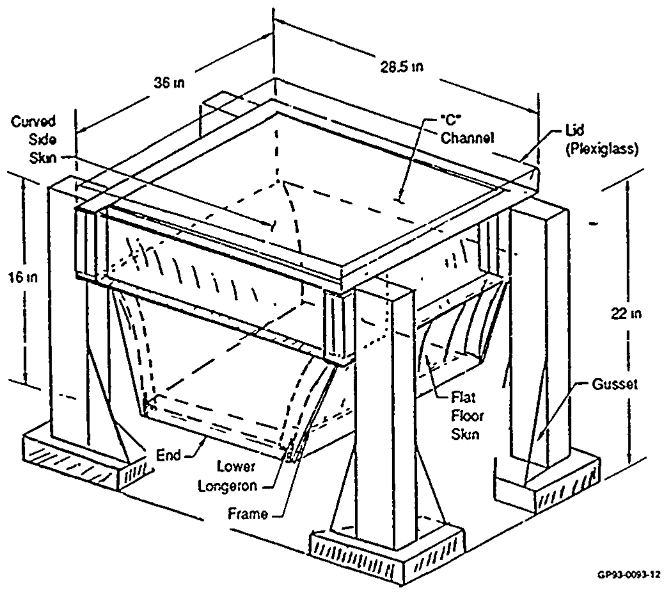
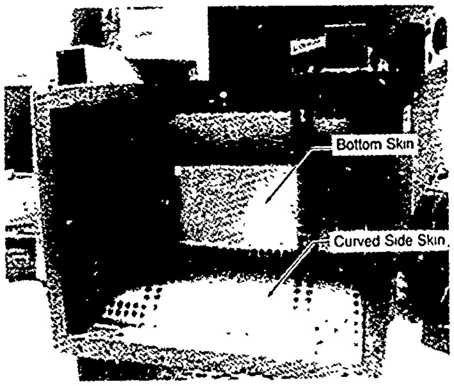
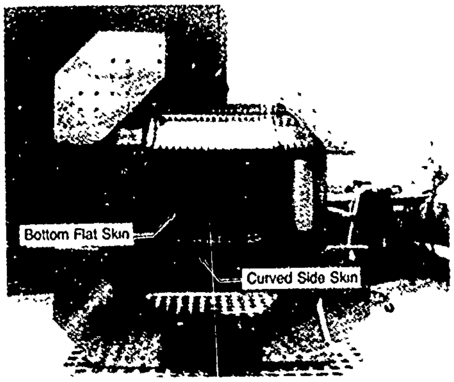


Figure 12. Representative Tank Section (Task VI)



Plan View



Bottom View

GP93-0093-13

Figure 13. Representative Tank Section – Task VI

CORRELATION OF THEORY AND EXPERIMENT

A few key results are given to show the breadth of the work, while significantly more details are given in our two major reports, References 4 and 6.

o Parallel Panels

We studied many cases of flat parallel panels and are showing these together here. The fluid-structure interaction vibration theory for parallel flexible panels accurately predicts the test results as shown in Figures 14 and 15. Figure 14 shows parallel side panel frequencies versus fluid depth as calculated from our theory and those found experimentally in our earlier IRAD. The results are for parallel panels vibrating in-phase, thus representing antisymmetric tank modes. Direct panel excitation was used so that both in-phase and out-of-phase (symmetric) motion was found in those tests. In-phase motion is more likely to occur in moving base cases which is our analogy for environmental vibration. It is particularly accentuated for nearly identical panels and odd lobed modes in moving base excitation.

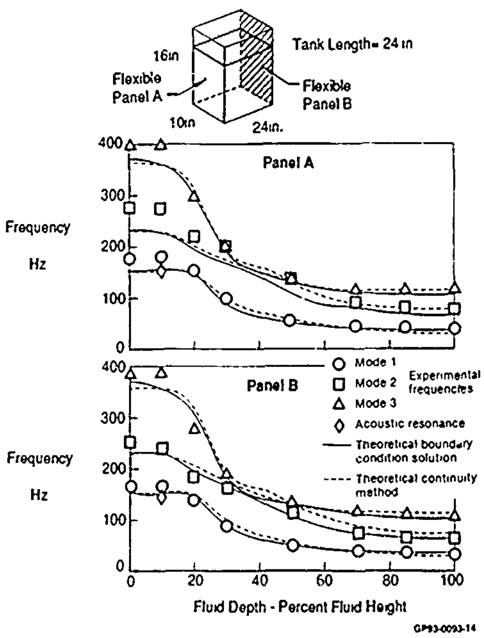


Figure 14. Parallel Vertical Panel Vibration – IRAD Tank In-Phase Motion

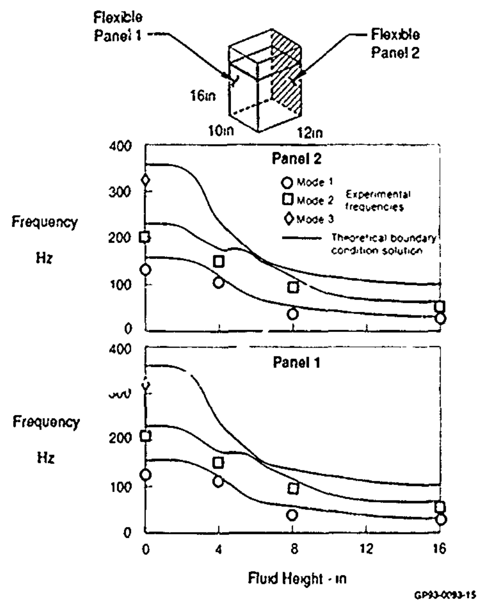


Figure 15. Parallel Vertical Panel Vibration – CRAD Tank In-Phase Motion

During these IRAD tests, the fluid depth was varied from 0 to 16 inches and the tank length was set at 3, 6, 16 and 24 inches. The tank length was set at 24 inches for the case shown in Figure 14. Two fluid calculation methods were used in the correlation, one we call the Boundary Condition Method, BCM, and the other we call the Theoretical Continuity Method, CM. Both techniques accurately predict the variation in frequency with fluid depth. We concentrated on BCM because it gave a better correlation with measured frequencies for closely spaced walls.

Figure 15 gives similar results for parallel side panels tested under the most recent CRAD, Reference (6), compared against only the BCM vibration results for parallel side panels. However, these tests were performed with the new tank fixture, as described previously, which had a fixed tank length of 12 inches. Moving base excitation was used in the tests, hence only in- phase odd lobed modes were predominantly excited. Again, our predictions are quite accurate for the variations in resonant frequencies with fluid depth.

If panel fatigue can be predicted with reasonable accuracy from strain response, then the key to a successful approach is accurate prediction of panel strain response. Measured linear and nonlinear strain response are compared to predictions for parallel side panels in Figures 16-17. Figure 16 presents sinusoidal results, whereas Figure 17 shows results for narrow band random excitation. Linear predictions of panel strain and fatigue were reasonably reliable using a closed form analytical approach. For the nonlinear region, a semi-empirical method was used when the deflection exceeded one panel thickness.

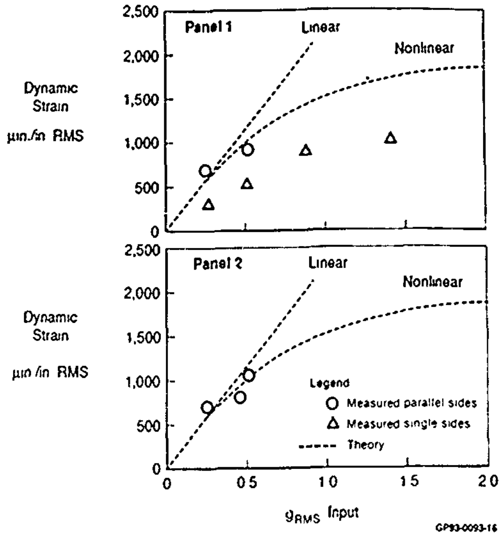


Figure 16. Parallel Side Panel Strain Response
Sine Excitation – Mode 1
Panel Thickness = 0 063 In 16 0 In Fluid Depth

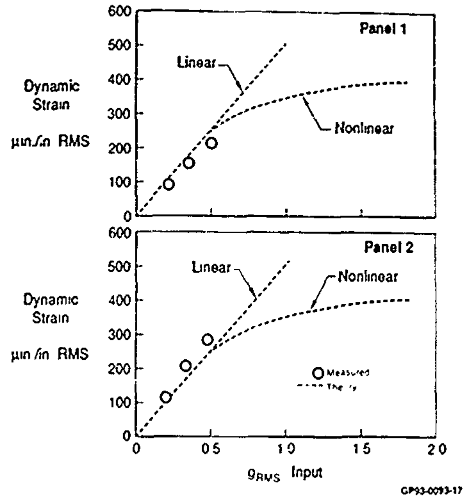


Figure 17. Parallel Side Panels Strain Response – Narrowband Random
Panel Thickness = 0 063 In 16 In Fluid Depth

Figure 16 presents measured and calculated strain response versus sinusoidal base excitation level for a pair of parallel side panels at full fluid depth 16 inches. Both linear and nonlinear calculations are shown in this figure, with our analysis showing a linear region below input levels of 0.3 g rms for both panels. The experimental data tends to validate this behavior. Shown also on Figure 16 are single side panel strain response points. Note the marked increase when two walls are excited simultaneously. This suggests a reduced fatigue life for parallel walls because the fluid cross coupling further accentuates dynamic response of the two panels.

Figure 17 is analogous to Figure 16 with narrow band random base excitation. The bandwidth was centered on the resonant frequency. The figure compares calculated and measured narrow band strain response of parallel panels at full fluid depth. Again, our theory is quite accurate in predicting the strain response of the parallel panels to a given excitation.

A summary of the sine fatigue tests for the parallel flat panels is shown in Figure 18. The dynamic bending strain of the panels at failure is compared to the fatigue theory which was correlated with the beam tests. The panel test results compare well with the theory for the zero preload case, since little prestrain was noted in the panels. This figure also shows that the combination of static preload sharply reduces fatigue life. Thus, this combination of loading reduces fatigue life over either effect taken independently. The results also suggest the fatigue life of two parallel walls is less than single walls because of the added strain induced by fluid cross coupling.

o <u>Curved Panels</u>

Curved panels attached to the bottom of the 12 inch deep tank were tested. Adapters were added to the flat surfaces of the tank to provide a slope along both of the 16 inch sides, while a curved surface was attached to each of the 10 inch sides to complete the cylindrical shape. The curved panel was placed against the adapters. This same framing was used in reverse on the other side of the panel so that the original flat picture frames were again useable. Calculated and measured frequency versus fluid depth are compared in Figures 19 and 20.

In Figure 19, the results reflect an initial configuration which has a slight error in radius of curvature, 125 inches rather than 72 inches as desired. This was tested and analyzed to provide additional data. Trends for two vibration modes are shown for the test data and for the computations based on the closed form Raleigh solution. Fair correlation is seen.

New adapters were made with the proper radius of curvature, 72 inches, and the tests were re-run. The test results are compared against calculations from NASTRAN based vibration coupled to our fluid-structure code in Figure 20. Here the first three modes show rather close correlation. Strain response comparisons are given for this latter configuration in Figure 21, comparing both the NASTRAN and Raleigh vibration methods, with the NASTRAN results being slightly better.

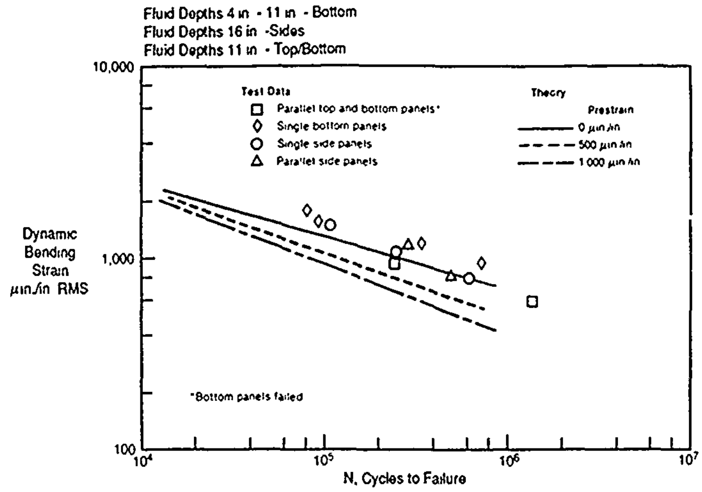


Figure 18. Fatigue Results Parallel Panels
Sinusoidal Excitation

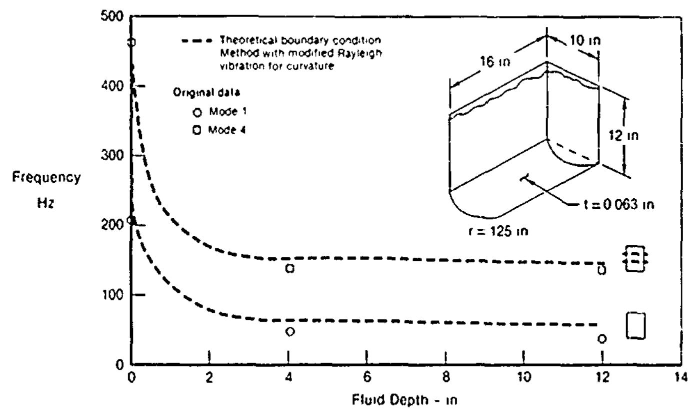


Figure 19 Comparison of Theoretical and Experimental Frequencies vs Fluid Depth
Curved Bottom Panel Radius of Curvature = 125 In

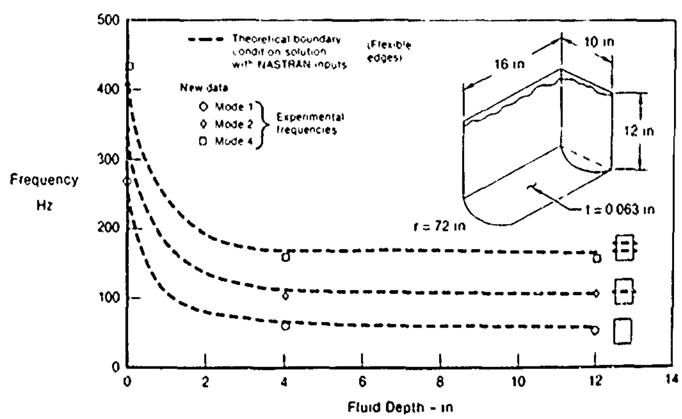


Figure 20. Comparison of Theoretical and Experimental Frequencies vs Fluid Depth
Curved Bottom Panel Radius of Curvature = 72 In

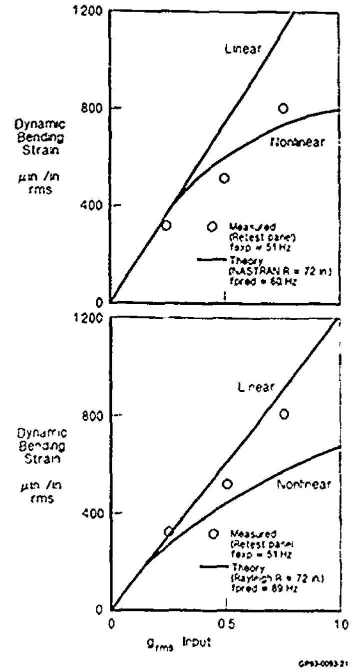


Figure 21. Comparison of Experimental vs Theoretical Strain Response
Curved Bottom Panel Sine Excitation – Mode 1
Radius of Curvature = 72 In 12 In Fluid Depth

Fatigue results for the curved panels are compared against fixed edge beam data in Figure 22. Close correlation is shown between the beams and the curved panels, as was the case for the flat panels. The critical strain areas were again similar to the flat panels, which is attributed to the shallow curvatures employed.

o Stiffened Panels

Adding a stiffener to a thin panel effectively raises the general panel stiffness properties and creates bays. Both features inherently raise the natural frequencies, which in turn tends to increase fatigue life. We evaluated ways of applying our methods to flat and curved panels which were stiffened by a single member. Panel thickness and stiffener orientation were varied. Too many cases were run to show here in detail, but some key observations can be given. The vibration results using our flat or slightly curved panel approach can reasonably well define most of the principal bay modes. Modes that can be missed are those which involve stiffener elastic or mass effects. These modes are generally involved in higher modes. The NASTRAN approach is better if greater detail is needed, or if better accuracy is needed in higher modes. Fatigue results for stiffened panels under random excitation are shown in Figure 23, where comparison to a beam fatigue curve is given. Close correlation is seen. Most of the failures were in the skins, while in a few cases the stiffeners also cracked.

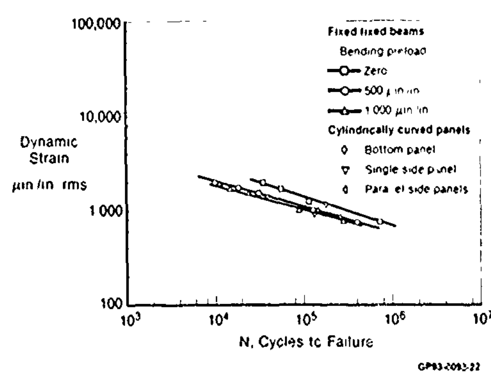


Figure 22. Fatigue Results for Cylindrically Curved Panels
Sinusoidal Excitation

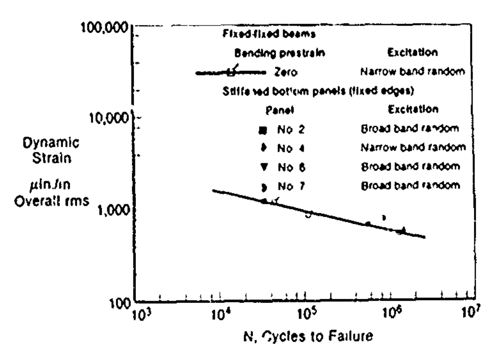


Figure 23. Stiffened Panel Fatigue Results
Random Excitation

o Nonlinear Panels

Many parameters were investigated under this task to further evaluate nonlinearity from membrane stiffening and large amplitude excitation. The depth of the original tank was increased from 12 inches to 24 inches for increasing the fluid head. Large static pressures and combinations with low frequency oscillatory pressure were used to amplify membrane effects. Likewise, random excitation was explored in more depth than in the prior work of Reference 4. This effort added considerable confidence to our approach, but it is too voluminous to be presented here.

o Sealants, Bags, Foams

We assessed the effect on fatigue of applying a layer of sealant to a panel, of placing a bag in the tank, and of placing a standard anti-ballistic foam volume in the tank. While the details are given in Reference 6, we can say here that the addition of these items is helpful.

The sealant layer was applied to the panel on the "wet" side as it would be in an actual application. Spray-on and direct application were used employing polysulfide and polyurethane. Mass effect, slight stiffness increase, and slight damping increases proved beneficial to fatigue life.

The bag was specially made to fit the entire cavity of the smallest tank. It was secured only at the top and rested against the bottom panel. The bag added some apparent mass and slightly more damping than the spray-on sealant for panel mode 1. In the higher modes, the bag appears to reduce response considerably, hence it helped extend fatigue life.

The foam had several effects. It was inserted to fill the cavity and was slightly larger than the actual tank cavity as is done in standard application. Thus, it added slight mass, damping and stiffness effects, and it also created a slight preload. These factors are all beneficial in extending fatigue life.

o Representative Tank Section

The objective of this study was to apply our method to a larger configuration, representative of internal fuel tank structure. Simplified analyses were used initially to develop a design. As design and fabrication proceeded, a highly detailed NASTRAN model was developed and used to confirm the simpler studies. Likewise, both methods were used in correlation studies employed during vibration, strain response and fatigue testing. Figure 24 shows a NASTRAN result for the dry case in which the overall tank modes 1 and 6 are respectively lower tank skin modes 1 and 2. Figure 25 compares the first lower skin mode as calculated and measured for a full condition of the tank.

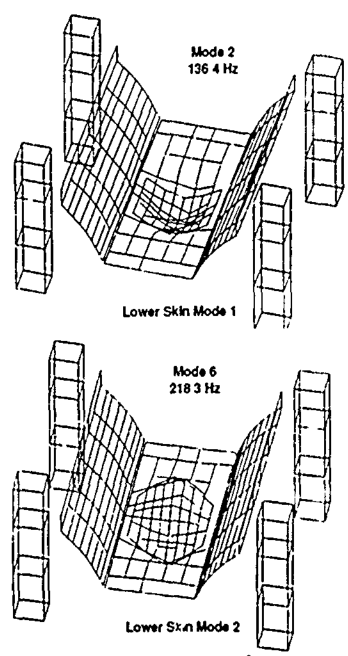


Figure 24. Entire Tank Mode Shapes (Modes 2 and 6)
Dry

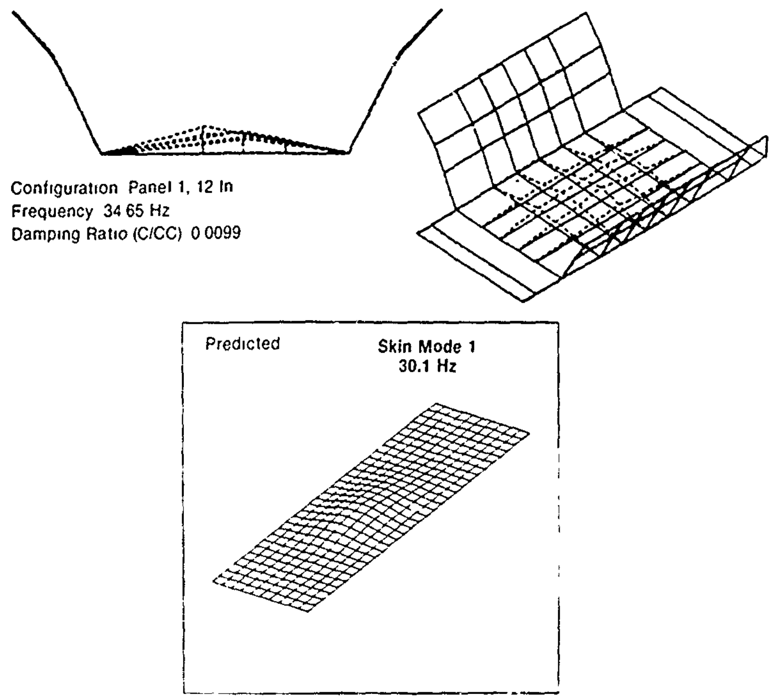


Figure 25. Comparison of Predicted and Measured Modes
Fluid Height - 12 In Bottom Tank Skin

Four fatigue failures were obtained for the tank bottom skin. Three of the bottom skins were sealed only at fasteners and joints by standard methods. A fourth panel was coated with polyurethane sprayon. All four tests were conducted with broadb^nd random excitation encompassing the first several modes. Also, a static pressure of 1 psi and an oscillatory pressure of 0.5 psi at 1/4 Hz were simultaneously applied. The failures agreed with beam tests and individual panel tests, as shown in Figure 26. The panel coated with polyurethane showed no leakage though the panel cracked similarly to the uncoated panels. This suggests that the coating reduces leakage.

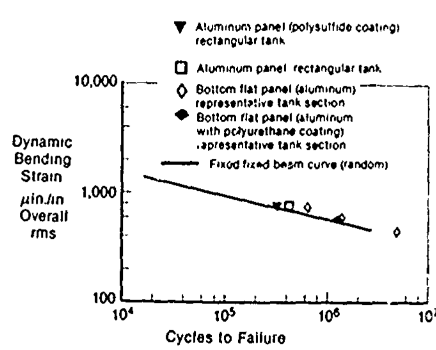


Figure 26 Flat Bottom Panel Fatigue - Random Excitation
Task VI - Representative Tank Section

o General Results

Nomographs are included in Reference 6 for rapid estimates of frequency, strain and fatigue life. These are designed to supplement the computer code. They cannot be covered in the span of this paper. However, one curve is given to provide a high confidence factor in the method, Figure 27. It gives the designer a broader view of calculation accuracy using the Rayleigh method for a general group of the panels tested.

A group of typical test points that provide a rather wide coverage of the overall ε-N range in this work was selected. The strains corresponding to the excitation levels used in the fatigue tests were calculated as was the fatigue life. Thus for each point a calculated strain ε_c and a measured strain ε_m is known, as are the calculated and measured values of the cycles for failure, N. In Figure 27, the calculated value of N, N_c is plotted versus the measured value, N_m. A 45° line is drawn to show ideal correlation. Note that the deviation from the 45° line is within ±10%. A similar comparison of the calculated to measured strains, ε_c and ε_m, is plotted. Again, a 45° line is drawn and the data all falls within ±10% deviation. The final part of the plot shows the measured values of ε_m vs N_m compared to the calculated values ε_c vs N_c. The majority of the data is for low values of static bending preload, while one point is a highly preloaded case where the bending preload is 2000 μ. This was selected to show the accuracy for one highly preloaded case.

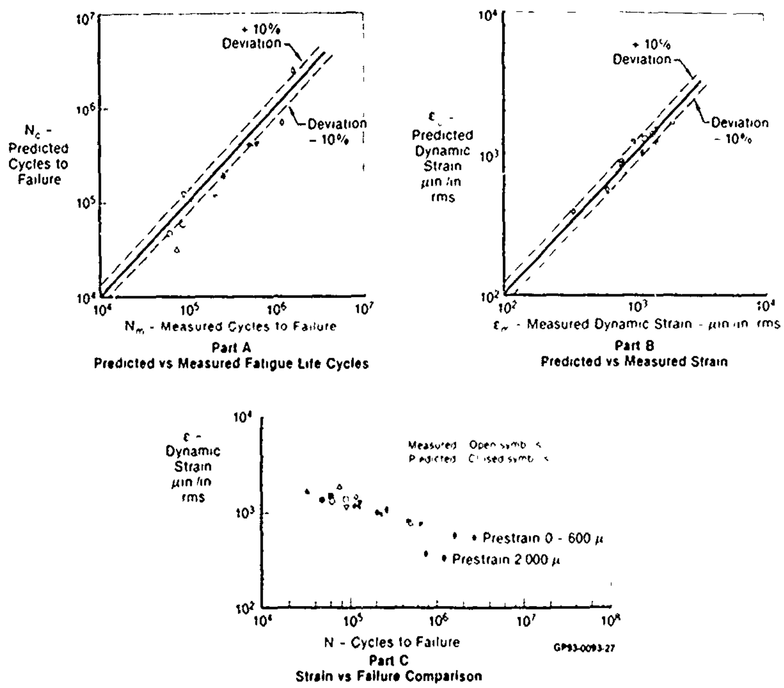


Figure 27. Panel Fatigue Prediction Accuracy – Sine

CONCLUSION

The method has been successfully extended to realistic structure and is now ready for application to full scale configurations. It should be applied to composite structures to extend our work on metal structures. The original thesis that the coupled fluid-structure interaction process causes a dramatic change in fuel tank skin dynamics leading to reduced fatigue life, has been carried further. The combination of this higher frequency loading aggravates the fatigue life based on maneuver load spectra. Prior investigations have omitted these loads in design practice. This technique should be used in the early design stage to develop adequate structure to avoid premature fatigue and leakage, thereby reducing hazardous conditions, aircraft repair tie-ups, and added costs. Similarly, structural updates and repairs should be evaluated for the same reasons. It is hoped that the U.S. Government and our NATO allies can make use of this methodology in the battle against fuel tank leakage. We have worked closely with the sealant technology under development in Reference 16 and the certification method of Reference 17 to ensure tie-in with closely related research.

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INTEGRAL FUEL TANK CERTIFICATION & TEST METHODS

by

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SUMMARY

Fuel tanks make up a significant structural volume of present aircraft designs. Life cycle costs and the repair of fuel tank leaks are significant. This paper describes the efforts accomplished, and now in progress, to develop methods to certify the fuel containment integrity of future USAF aircraft. The methods use the idea of combining the aircraft structural durability testing requirements with a fuel tank certification requirement. The application of this concept during the development phase of a new aircraft design will enable deficiencies in fuel tank sealing designs to be discovered early, before production begins. The work accomplished to date using C-130 wing fuel tank components, has shwon that this approach is possible and does provide valid results. The requirement to employ environmental exposures, including the use of actual jet fuels, and not water or simulants, is emphasized.

INTRODUCTION

Fuel leaks from aircraft integral tanks are a high cost item. These costs are incurred directly by the maintenance required to repair leaks and return the aircraft to flight status, and indirectly by the reduction in aircraft availability. Current technology concerning structural design to ensure leak-free integral fuel tanks is unchanged from that of 20 years ago. New sealants and fasteners have been developed, but little work has been done to evaluate fastener/sealant systems for leak susceptibility. Current military specifications and other documents do not adequately cover the range of environments and conditions that must be included in a test spectrum to provide a reliable certification testing procedure for new military aircraft integral fuel tanks.

Commitment to a particular sealing method must be made early in the aircraft design process. The stress and design engineers must work closely with the sealing specialists. Unfortunately this cooperation has not always occurred. When a requirement to lighten a specific part or increase the space in a certain area is specified, the stress engineer can do so using established engineering practices based on analytical stress techniques and design formulas. Unfortunatley, sealing requirements are not as well defined and more than likely are based on previous experiences rather than on verified design analysis.

BACKGROUND

ESTABLISHMENT OF A FUEL TANK WORKING GROUP

Although the Air Force experience with fuel tanks has seldom been entirely satisfactory, it was not until problems with the F-111 aircraft in 1973, that a concentrated effort was started to study existing problems and to evaluate the potential for problems with new systems and future aircraft designs.

The F-111 problems were encountered in the fuselage integral fuel tanks. The serious fuel leak problems were found to be the result of reversion of the polyester sealant then in use. This resulted in loss of aircraft availability and the expense involved in desealing and resealing the aircraft.

In October 1976 a Fuel Tank Working Group was formed within the Aeronautical Systems Division (ASD). This group included members from the Air Force Wright Aeronautical Laboratories (AFWAL), now the Wright Research & Development Center (WRDC), including the Flight Dynamics Laboratory, Materials Laboratory and the Propulsion Laboratory, also included was the Air Force Acquisition Logistics Division (AFALD).

COMMITTEE CONCLUSIONS

1. The aircraft manufacturers have recognized the fuel tank leak problem and most have taken or are taking steps to reduce them.

2. The following techniques have shown excellent fuel containment characteristics which could offset any increased manufacturing costs that might be incurred.

   a. Adhesive bonding such as used on the F-102 and F-106.
   b. Use of automatic rivet machines, interference fit fasteners and gap tolerance control.
   c. Advanced welding techniques on selected materials.

3. Air Force handbooks, specifications, and data requirements have deficiencies in them and need correcting.

4. Air Force laboratory testing has consisted mainly of materials testing. There is a need for complete assembly testing in an environment equivalent to that encountered in flight, to determine best sealing designs.

5. The Air Force specification, MIL-S-8867, at present requires very little fuel tank testing. Very often this minimum requirement is waived and no fuel tank testing is done.

6. Airframe manufacturers have expressed the opinion that slosh and vibration requirements are not realistic. Such tests often accomplish nothing other than to damage tank and aircraft structure.

These are but a few of the major conclusions which resulted in the initiation of efforts within WRDC to solve aircraft fuel tank technology problems.

CURRENT FUEL TANK REQUIREMENTS

The entire series of MIL-A-00867 documents, including the new MIL-PRIME series, indicates the Air Force's increasing concern with aircraft fuel tank problems. Unfortunately, the current requirement, which specifies that a "full-scale representative tank section" be durability tested for two lifetimes, is imposed so late in a new aircraft program, that corrections of any design or fuel sealing systems faults detected at that time, would cause significant delays in a production program.

The present military specifications for fuel tank testing do not contain the complete environmental spectra experienced by aircraft. These conditions are necessary to simulate the actual real life service exposures of fuel tanks. The specifications require testing of fuel tank structures with the normal pressure loadings seen in service along with the flight and ground loading required to satisfy fatigue and damage tolerance requirements. The specifications do not include the use of fuel, or the application of temperature and humidity effects.

Slosh and vibration testing is generally required for qualification when flexible bladder cells are installed in wing and fuselage compartments. Although not specifically designed for integral fuel tank testing, slosh and vibration tests have been utilized in integral fuel tank programs. The results of these programs have indicated that such tests caused extensive structural damage to the internal structure with essentially no fuel leaks.

Even with these specifictions present, many manufacturers have not complied with the requirements. The two reasons often stated for this lack of compliance are:

1. The general opinion that the use of similar successful design practices is adequate, and

2. Fuel tank durability testing is too far along in the total development of the aircraft to permit corrective actions before prototype aircraft are flying.

CERTIFICATION METHOD DEVELOPMENT

OBJECTIVES

It was decided to develop a method of certifying aircraft integral fuel tanks which could be accomplished early in the design process. The method would depend on the use of large integral tank structures developed in the design verification phase of a new aircraft program.

The method would accomplish the certification of the sealing systems, and the normal fatigue requirements, using one test component. The total time required to do such a combined test would not exceed that required for the structural certification test. Testing would use actual fuel along with the correct environmental exposures for the aircraft type being tested.

The approach to achieve these objectives involved truncating both the durability spectrum and the environmental spectrum. The final spectrum would result in a certification test time which was shorter or at least of equal length as the normal durability test. Only loads that were considered detrimental to fuel tank integrity and durability, and those environmental conditions that would effect the sealant materials, were retained.

FUEL TANK ENVIRONMENTS

Many of the environmental conditions that are experienced by aircraft integral fuel tanks are common to aircraft of all types and sizes, but not necessarily to the same extent. A significant number of other environmental conditions affect only certain aircraft types.

There are some ground load, flight load, thermal environments, and other conditions that are common for all military aircraft regardless of classification, but not necessarily of equal significance. A summary of these conditions is shown in Table 1.

Table 1: CONDITIONS COMMON TO ALL MILITARY AIRCRAFT

GROUND LOADS	THERMAL EFFECTS
Taxi	Solar heating
Take-off	Low ground temperatures
Landing	Low flight temperatures
	Rapid temperture changes

FLIGHT	CHEMICAL	OTHER
Maneuver loads	Fuel	Altitude
Gust loads	Water	Airframe aging
Fuel inertia	Humidity	

With the wide variety of military aircraft types in service, it is understandable that the environmental conditions to which they are exposed would vary considerably. High performance fighter aircraft would see different temperature exposures during high speed flight which would not be experienced by a cargo type aircraft.

A list of environmental conditions that might vary by aircraft type is shown in Table 2.

Table 2: CONDITIONS THAT VARY FOR DIFFERENT AIRCRAFT TYPES

STRUCTURAL ATTACHMENT LOADS	THERMAL EFFECTS
Landing gear	Aerodynamic heating
Engines	Engine heating
Engine pylons	Gun heating
External stores	High fuel temperatures
SPECIAL LOAD CONDITIONS	**PRESSURES**
Catapulting	Manufacturing test
Carrier landings	Ground fueling
Emergency arrestment	Aerial refueling
	Operating
FLIGHT LOADS	**VIBRATIONS**
High Mach no's.	Engine
High 'G' loads	Sonic
Combat maneuvers	Flutter
	Guns/Stores

SUMMARY OF CRITICAL ENVIRONMENTAL ELEMENTS

A critical environmental element is considered to be a condition that causes the greatest amount of structural deflection in the fuel tank, one that causes the greatest degree of fastener load, or loosening, or one that causes the greatest amount of structural material or sealant material degradation.

No one environmental condition is the single ingredient in degradation of fuel containment integrity. It would appear that the combination of structural loading, fuel inertia, fuel tank pressures, thermal and chemical effects, and possibly vibration and altitude effects, have detrimental influences on fuel containment integrity. On an individual basis, the thermal and chemical environments contribute most to degradation of fuel containment integrity. The relative importance of these environmental conditions in regards to fuel containment is dependent on the type of sealing material utilized.

It is necessary to include some, but not all, of these conditions in the certification program. The conditions can be divided into two categories, load spectra and environmental spectra. The loads spectra result in structural deflections and stresses, while the environmental spectra result in changes, such as aging, to the sealing system materials.

DEVELOPMENT AND VERIFICATION OF THE DURABILITY SPECTRA

It is not practical to test an aircraft fuel tank using a spectrum equivalent in time to the actual life of the aircraft. It is necessary to shorten the spectrum yet still have the same total effects on the fuel tank as would be seen in the lifetime of the aircraft. Such a truncated spectrum can be applied to the test article in a reasonable amount of time early in an aircraft program. Some aircraft programs may require both a short-term component test for fuel tank certification, because of aircraft size, and a long-term durability test on a full-scale article. Information learned from these early truncated spectrum tests can be used to revise the production fuel tank design and improve the structural integrity of the full-scale durability test article.

To achieve the goal of developing a cost-effective procedure for fuel containment integrity certification, a method was devised which would permit fuel containment testing to be accomplished simultaneously with normal durability testing. This idea is based on the assumption that most of the fatigue critical loads are also critical loads for fuel sealing certification. Cyclic loading combined with realistic environmental exposures are the requirements for this test approach. A fuel tank test will normally require repairs for leaks just as a fatigue test will require repairs for fatigue damage. To meet the goal of having the combined test not exceed the time span of the normal durability test, the loads spectrum must be truncated for use in the combined test. The approach to

the truncation was to exclude load cycles producing stress changes below certain values and to also exclude load cycles thought not to have detrimental effect on the fuel tank sealing integrity.

The load spectrum truncation method was developed for three basic aircraft fuel tank structures, a fighter wing and fuselage, and a transport wing. The goal established was a 20% reduction in the number of load points from the baseline durability spectrum. This reduction allows time for the special requirements of the fuel tank sealing certification, such as leak inspections, fuel changing, heating/cooling cycles, etc. The final loads spectrum must result in crack growth generation closely matching the original spectrum, and no loads which result in excessive or representative joint deflections can be excluded.

To maintain a uniform method of truncation for the three loads spectra, and to retain loads detrimental to fuel tank integrity, it was decided to use low stress level edit truncation, as opposed to gust and maneuver load deletion techniques. The three criteria used in the selection of the edit truncation level were:

1. The amplitude of the excluded stress changes shall not exceed the fatigue endurance limit for the material at a nominal KT of 3.

2. The da/dn rate corresponding to the amplitude of the excluded stress levels shall be at least two orders of magnitude below the nominal da/dn rate corresponding to the maximum spectrum stress level at a typical control point.

3. A reduction of approximately 20% in the number of load cycles per service life from the durability test spectrum, while maintaining an approximately equal damage rate.

Coupon verification testing was conducted to ensure that the new loads spectrum reproduced the same effects as the baseline spectra. The coupon tests were conducted for all three fuel tank types, fighter wing and fuselage, and transport wing. In all three cases, the coupon testing did verify that the specimens tested with the fuel tank certification load spectra had caused similar fatigue lives as the original baseline spectra. A comparison of the baseline spectra to the modified spectra is shown in Fig. 1.

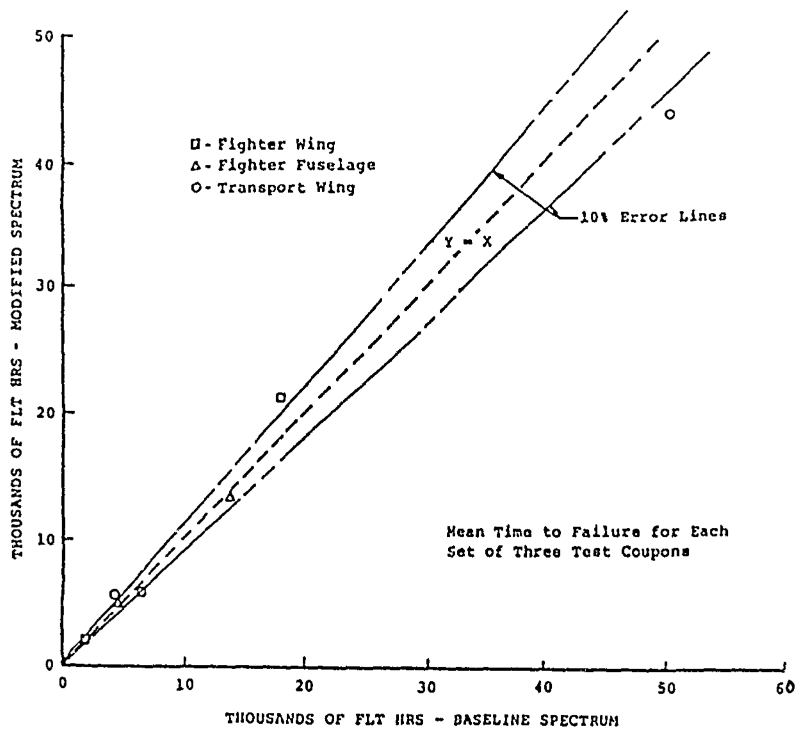

Fig. 1

When examining these environmental conditions for an aircraft the following must be considered:

1. Design criteria
2. Projected ground environmental exposures
3. Projected flight environmental exposures
4. Type of fuel
5. Frequency of refueling
6. Rate of heating

A combination of these conditions will result in an environmental exposure spectrum. As was necessary with the loads spectra, this spectra must be manipulated or truncated to result in a reasonable test time when combined with the loads spectra.

The steps involved in developing the real-time environmental exposure spectrum and the final truncated spectrum were as follows:

1. Develop in-flight temperature data using mission profiles.
2. Develop ground temperature data using expected basing information.
3. Develop a humidity profile for the expected basing.
4. Assemble all temperature and humidity data and retain all data which is detrimental to sealing materials.
5. Apply Arrehenius' Law to truncate the exposure times at lower temperatures to shorter times at higher temperatures.
6. Make assumptions based on test data to further reduce total test time.

The in-flight temperature exposure history and the on-the-ground exposure history were generated by computer programs. The fighter aircraft exposures were based on the F-16 with a design life of 8,000 flight hours and a projected service life of 15 years. The design life for the transport aircraft was based on the C-130H and was assumed to be 40,000 flight hours and a projected service life of 30 years.

In-flight temperature and humidity data were generated for the fighter wing and fuselage and the transport wing. The computer program used defined the aircraft life in terms of up to 12 mission types, each of which may have up to 20 Mach-altitude "boxes". The program selects a Mach number and an altitude within each box by assigning a uniform probability to each. It is unlikely an aircraft is flown precisely at design, mission profile Mach numbers and altitudes. This approach was felt to be more realistic than simply using design Mach-altitude points.

The ambient temperature at the selected flight condition is obtained from a skewed Gaussian distribution with the 1962 ARDC Standard atmosphere as the mean and the MIL-STD-210A Cold and Hot days as the 10th and 90th percentile points respectively. The adiabatic wall temperature is calculated from the selected Mach number and ambient temperatures. Also tabulated are the number of temperature exceedances and the time spent at, or above, temperature. Table 3 shows the in-flight temperature data generated for the F-16. Table 4 presents the data for the C-130 integral wing tanks.

The data shows that over 60% of the projected C-130 in-flight skin temperatures are at 15°F or below, whereas on the fighter, only 40% of the time at temperature is at 15°F or below. It would appear that the transport temperatures would not cause extreme degradation of a polysulfide sealant; however, the larger deflections experienced by a transport wing during a long cold soak could cause the sealant to crack or lose adhesion.

The ground exposure data computer program generated a weather history from statistical weather data for each basing location of interest. Five basing locations were used: Kadena, Okinawa (Tropical); RAF Upper Heyford (Northern Europe); Nellis AFB (Hot Desert); Homestead AFB (Subtropical); and Moron de la Fiontera (Southern Europe). These bases were used for both aircraft types. The computer program used random number generation that assigned varying lengths of time at each base. The exposures were accumulated at each base including time in hangers, and totaled. The temperature results for the F-16 and C-130 are presented in Tables 5 & 6. Tables 7 & 8 show the projected humidities for the F-16 and C-130.

It is necessary to reduce the total exposure times to maintain a reasonable total test time compatible with the time required to apply the loads spectrum. A rationale for exchanging time and temperature for equivalent degradation of the sealant materials was established. Test data suggests that the Arrhenius' Law (ref. 11) and Feiser's "activation energy" principal (ref. 12) hold true for polymeric based fuel tank sealants. These two references show that chemical reactions in organic systems are a linear function of the absolute temperature. A rough generalization is that the rate is doubled by a rise in temperature of 10°C. It was further assumed that no significant degradation of the sealant material occurs under continuous exposures to temperatures below 120°F.

Note: Times shown for each temperature are times at or above the particular temperature.

Table 3: PROJECTED F-16 FUEL TANK STRUCTURAL TEMPERATURES DURING FLIGHT

Wing Skin Temperature (°F)	Hours	Fuselage Temperature (°F)	Hours
295.0	0.0	315.0	0.0
285.0	0.0	305.0	0.0
275.0	0.0	295.0	0.0
265.0	0.0	285.0	0.0
255.0	0.117	275.0	0.7833
245.0	1.695	265.0	3.217
235.0	4.227	255.0	6.300
225.0	7.115	245.0	10.60
215.0	12.23	235.0	15.19
205.0	18.77	225.0	22.94
195.0	27.0	215.0	30.08
185.0	39.25	205.0	39.64
175.0	60.67	195.0	54.99
165.0	88.41	185.0	72.81
155.0	123.7	175.0	99.51
145.0	181.1	165.0	129.0
135.0	265.8	155.0	176.6
125.0	388.9	145.0	245.6
115.0	545.0	135.0	347.6
105.0	753.0	125.0	487.5
95.0	1018.0	115.0	667.6
85.0	1354.0	105.0	901.2
75.0	1739.0	95.0	1189.0
65.0	2182.0	85.0	1547.0
55.0	2647.0	75.0	1961.0
45.0	3144.0	65.0	2414.0
35.0	3705.0	55.0	2911.0
25.0	4281.0	45.0	3411.0
15.0	4831.0	35.0	4005.0
5.0	5380.0	25.0	4561.0
-5.0	5964.0	15.0	5101.0
-15.0	6529.0	5.0	5701.0
-25.0	7008.0	-5.0	6281.0
-35.0	7417.0	-15.0	6786.0
-45.0	7695.0	-25.0	7210.0
-55.0	7821.0	-35.0	7570.0
-65.0	7869.0	-45.0	7764.0
-75.0	7895.0	-55.0	7842.0
-85.0	7906.0	-65.0	7882.0
-95.0	7912.0	-75.0	7898.0
-105.0	7917.0	-85.0	7908.0
-115.0	7920.0	-95.0	7914.0
-125.0	7912.0	-105.0	7917.0

Table 4: PROJECTED C-130 FUEL TANK STRUCTURAL TEMPERATURES DURING FLIGHT

Wing Skin Temperature (F°)	Hours (Per Thousand Hours)
145.0	0.0
135.0	0.291
125.0	2.052
115.0	6.178
105.0	11.25
95.0	19.24
85.0	25.47
75.0	35.41
65.0	45.91
55.0	52.00
45.0	62.60
35.0	66.20
25.0	90.10
15.0	100.8
5.0	102.6
-5.0	101.0
-15.0	91.20
-25.0	73.00
-35.0	53.00
-45.0	39.40
-55.0	19.50
-65.0	2.800

Table 5: F-16 PROJECTED GROUND STRUCTURAL TEMPERATURES

Temperature (F°)	Hours Wing	Hours Fuselage
190.0	0.0	0.0
180.0	0.0	0.0
170.0	0.0	0.0
160.0	0.0	0.0
150.0	1944.0	0.0
140.0	1944.0	0.0
130.0	3038.0	3888.0
120.0	4276.0	2894.0
110.0	7046.0	3340.0
100.0	6470.0	11774.0
90.0	9528.0	15703.0
80.0	24624.0	20589.0
70.0	22084.0	25972.0
60.0	21700.0	19920.0
50.0	10756.0	11059.0
40.0	17222.0	15494.0
30.0	115.0	115.0
20.0 ↓ -60.0	NEGLIGIBLE	

Table 6: C-130 PROJECTED GROUND STRUCTURAL TEMPERATURES

Wing Skin Temperature(F°)	Hours (Per Thousand Hrs.)
-65 ->20	.35 estimated
21 ->40	216.4
41 ->60	470.6
61 ->80	250.5
81 ->100	39.8
101 ->120	23.1
120 and above	Negligible

Table 7: F-16 PROJECTED GROUND HUMIDITY

Humidity Range (%)	Hours Wing	Hours Fuselage
0	9946	4968
10	7711	10317
20	12657	13399
30	14150	12295
40	7850	10382
50	8836	12242
60	12847	10826
70	8640	17683
80	27686	35107
90	17121	892
100	3804	2637

Table 8: C-130 PROJECTED GROUND HUMIDITY

Humidity Range %	Hours (Per Thousand Hrs.)
0 ->19	2.6
20 ->39	47.4
40 ->59	35.5
60 ->79	316.7
80 ->99	552.6
100	20.3

APPLICATION TO THE TRANSPORT WING SPECTRUM

The design criteria for the C-130 aircraft are as follows:

Minimum Temperature:	-65°F
Maximum Temperature:	160°F (50 hours maximum)
Maximum Fuel Temperature:	140°F
Tank Pressure:	Vented tank

The projected fuel tank temperatures for the C-130 during ground exposure, shown in Table 6, were used to establish the static fuel exposure environment. The maximum fuel temperature was used as the static exposure temperature. The data in Table 6 projects a maximum ground temperature not more than 120°F. It was assumed that no sealant degradation occurs on the ground. It is necessary to allow the sealant to become thoroughly

exposed to fuel to expand to its normal state. To accomplish this an exposure to 140°F for 672 hours was added to the spectrum.

The C-130 in-flight temperature data (Table 4) was reduced to a spectrum that can be easily applied in a short period of time. Arrhenius' Law was used to convert time-temp. exposures to a shorter exposure at a different temperature to produce equivalent sealant degradation. The fuel exposure profile was divided into two conditions, with fuel and without fuel. It was assumed that the tank would be dry one-half of the flight time when exposed to the design maximum temperature of 160°F. Fuel soak temperatures were set at the upper and lower extremes (140°F and 120°F) in order to allow sufficient time to insure that the sealant is fuel saturated. The dynamic spectrum time-temperature conversions are shown in Table 9.

Table 9: C-130 WING INTEGRAL FUEL TANK

Real Time Exposure			Equivalent Exposure Time	
Temp. °F	Mean Temp.	Hours	Hours	Temp. °F
		(Tanks Fueled)		
135-145	140	5.82	5.82	140
125-135	130	41.04	27.93	140
115-125	120	123.56	123.56	120
		(Tanks Dry)		
135-145	140	5.82	5.82	140
125-135	120	41.04	27.93	140
115-125	120	123.56	57.20	140
160	Design Criteria		50.00	160

Although the assumption was made for developing the exposure spectrum that the tanks would be empty one-half of the time, this is unlikely to occur in actual flight. The fuel tank test components are drained to one-quarter full instead of being completely drained.

The rationale for sub-zero temperature exposures is that there is no degradation of the sealant at low temperatures. An arbitrary time of 24 hours at -65°F for both static and dynamic exposures was selected. Due to the long time required to achieve 40,000 equivalent flight hours of structural loading, it was decided to eliminate any static temperature exposures and combine them with the dynamic temperature exposures. The 24 hours of sub-zero exposure were changed to 48 hours of exposure during structural loading. This is substantiated by the high percentage of exposure for the C-130 that is below freezing (Table 4).

A pressure spectrum was developed for the C-130 environmental spectrum even though the wing tanks are vented. The pressures were added to simulate the pressure heads that occur during flight due to maneuver loads above 1 'G'. An average 'G' maneuver for the C-130 is approximately 2 G's. This pressure head would be simulated by varying the tank pressure from atmospheric to 1.3 psig at a rate of one-half cycle per minute. Pressure excursions to 3.5 psig, representing a 4 5 G loading (C-130 limit load), are applied six times during each 40,000 flight hours. These 3.5 psig excursions do not occur when the structure is loaded to avoid an over stress condition.

Since the integral tanks experience humidity, water was added to the fuel based on the standard specification test for humidity resistance of elastomeric materials (MIL-S-83430). The test states that materials must be tolerant to 120 days exposure to 95% relative humidity at 160°F. The addition of 10 grams of free water per cubic foot of test tank volume will insure a minimum water vapor concentration equivalent of 95% R.H. at 160°F.

Actual aircraft usage consists of ground time followed by flight time. After each flight the aircraft is refueled. To simulate these conditions the test spectrum was divided into six test cycles with fuel changes each five days. Based on the previously mentioned procedure, the following environmental exposure spectrum was arrived at for the C-130.

1. Dynamic Exposure - Structural Loads and Pressures
   - 24 hours at -65°F with fuel
   - 112 hours at 140°F fuel changed after exposure
   - 24 hours at -65°F with fuel
   - 21 hours at 120°F with fuel
   - 6 hours at 140°F with fuel
   - 15 hours at 140°F ¼ full of fuel
   - 8.3hours at 160°F ¼ full of fuel

2. Humidity - 10 grams of water per cubic foot of tank volume.

3. Internal Pressure - Cyclic pressure from 0 to 1.3 psig at a rate of one-half cycle per minute. Six pressure excursions to 3.5 psig.

4. Repeat test cycle five times for a total of six cycles per 40,000 equivalent flight hours.

SUMMARY: ENVIRONMENTAL SPECTRA METHODS

Development of the environmental test spectra for the fighter and transport fuel tank verification testing required making several assumptions about the behavior of sealant materials exposed to fuel and temperature. These assumptions were:

1. Sealant deterioration rates are predictable by Arrhenius' Law;

2. Significant sealant degradation does not occur below 120°F;

3. Significant sealant degradation does not occur at sub-zero temperatures;

4. Humidity effects can be simulated by the addition of free water in the test tank; and

5. Cyclic exposure is necessary to simulate aircraft usage conditions.

These assumptions were verified by a series of coupon level tests. The effect of the various environmental exposures were evaluated using tensile, elongation, hardness, weight loss, and peel mechanical properties. The detailed results can be found in Ref. 5.

DESIGN OF THE FUEL TANK TEST COMPONENTS

Three basic fuel tank component designs were investigated; a fighter wing, a fighter fuselage, and a transport wing. The baseline aircraft chosen were the F-16 and the C-130 (See Fig. 2). The following requirements were used in making these selections:

1. They were existing designs.

2. They were in use in the current USAF inventory.

3. The aircraft employed integral fuel tanks.

4. Historical data about fuel leakage was available.

5. Fatigue data was available for the aircraft.

6. The integral tanks employed a polysulfide based sealant system.

7. Durability loads and environmental spectra data were available.

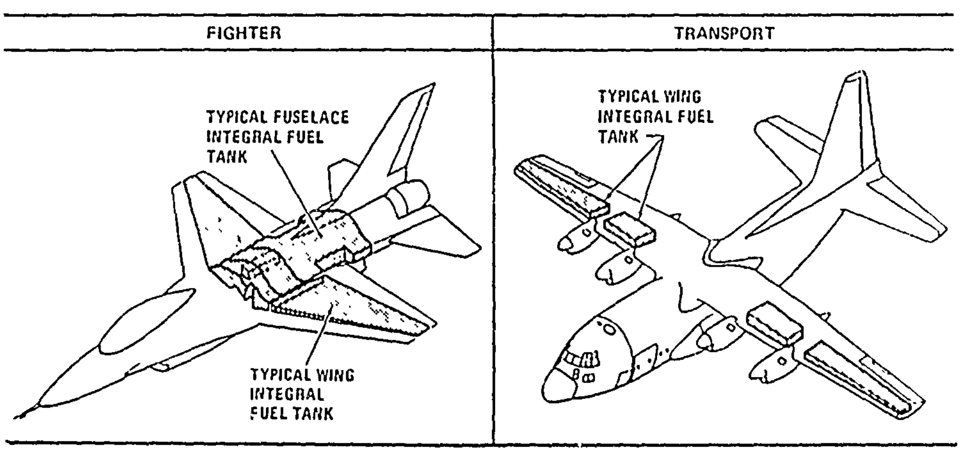

Fig. 2

The final design chosen for verification testing was the C-130 transport wing. This choice was based on the larger data base available for the C-130 and the large size of the component. The use of a larger component made the inclusion of known trouble spots, such as the flap attachment areas, easier to incorporate into the test component design.

C-130 WING TANK DESCRIPTION

The C-130 has four separate wing integral fuel tanks: two in each of the left and right outer wings. Additional fuel is carried in the wing center section in bladder fuel cells. The integral tanks are separated by a dry bay compartment located immediately behind the no. 1 and no. 4 engines. The boundaries of each integral tank, shown in Fig.3,

are the outer wing upper and lower skins, the front and rear spares, the inboard and outboard bulkheads. The main wing box is tapered in planform and thickness.

The outer wing upper and lower surfaces each consist of four machined, integrally stiffened skin panels that are joined by a single row of bolts at simple spanwise lap joints. The skin panels extend continuously from the outer wing station where the outer wing joins the center wing to the wing tip. The front and rear spars are built-up construction consisting of machined upper and lower caps, webs, and vertical stiffeners, all joined with fasteners. Integral tank end bulkheads consist of integrally stiffened webs attached to upper and lower caps, except at the inboard end, where the outer wing is joined to the center wing. At this location the web is integral with the upper and lower attachment fittings. Ribs inside the outer wing box structure are truss construction with the members joined to upper and lower rib caps. Most of the truss rib caps are attached to integral stiffeners on the wing upper and lower skin panels. At the end bulkheads, the caps attach to the flat skin portion of the integrally stiffened skins. The structural materials used in the detail parts of the wing box are 7074-T73 and 7075-T6 aluminum. After fabrication the parts are subjected to a chromic acid anodize surface treatment before application of a MIL-C-27725 surface finish. the wing tank structure is assembled with clearance-fit steel fasteners such as lockbolts, Hi-loks and screws. Aluminum rivets are used at such locations as spar and bulkhead web stiffeners.

C-130 TEST TANK DESCRIPTION

The section of the C-130 transport wing integral fuel tank selected for testing is shown in Fig. 3. It consists of a two spar box 180 inches long and 38 inches wide. It tapers in depth from approximately 21.5 inches to 18.5 inches. It represents the C-130 wing form Outer Wing Station (OWS) 144.0 outboard to OWS 326.0 except for the pylon fittings. T! pylon fittings are located further inboard on the actual aircraft. They were moved outboard on the test component. The test component is only about 1/3 the actual chord of the airplane wing. Shear flows in the component closely match those in the airplane wing. Besides the external loads, wing bending, shear, and torsion, provisions were made to apply pylon and trailing edge flap loads. The component also incorporated a dry bay which represents the outboard engine dry bay in the aircraft wing.

The integral fuel tank was sealed with a multiple barrier system throughout. MIL-S-81733 corrosion inhibitive polysulfide sealant was used in the faying surfaces and on the fasteners. All faying surfaces and voids were sealed, all fasteners were installed with sealant on the shanks, and, after assembly, sealant fillets (MIL-S-8802 sealant) were applied along all seams and over all fastenes on the fuel tank interior. A fuel-resistant polyurethane topcoat was brush applied over the MIL-S-8802 sealant. This top-coat met all requirements of MIL-C-83019.

ENHANCED TRANSPORT COMPONENT

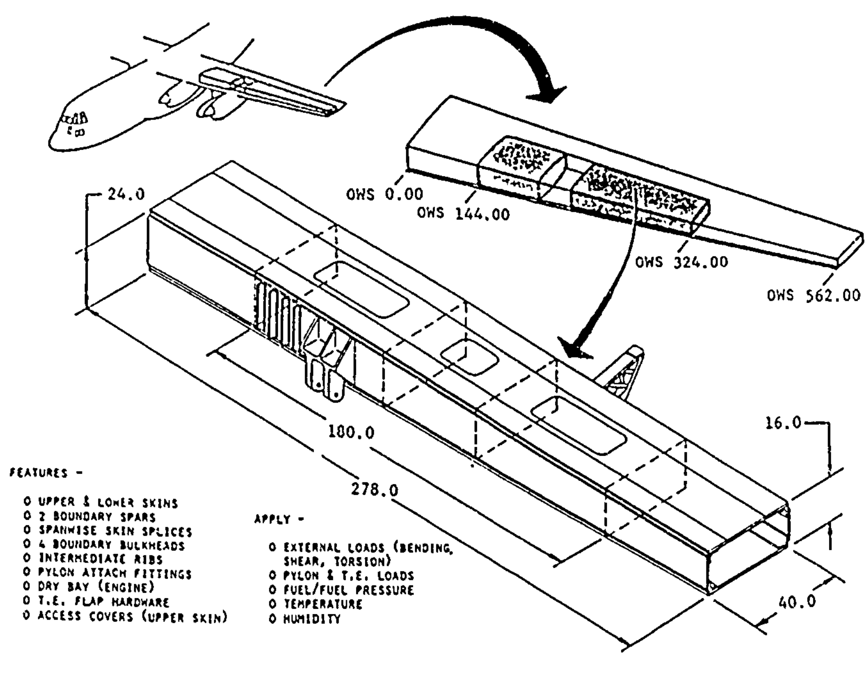

Fig. 3

TESTING OF FUEL TANK TEST COMPONENTS

TEST PROCEDURES

The primary objectives of the testing program are to verify the procedures developed for certifying fuel containment integrity, and prove the practicality of combining this certification test with those required for structural durability.

The testing program consists of the application of a normal fatigue spectrum to a C-130 wing tank test component to establish a baseline fatigue history. This testing was done at room temperature with no special environmental parameters added for fuel tank certification. The test component contained no fuel and no testing was done to verify its leak integrity. A second and third component will be tested using the modified loads spectrum combined with environmental exposures with, and without fuel. The results from the second and third test components will be compared to the first to evaluate how well the durability performance of the truncated spectrum simulated the baseline spectrum.

The procedure for each test is as follows:

1. A strain survey of structural loads.

2. Proof tests and leak tests with nitrogen, fuel and temperature conditions applied to the test component.

3. Preconditioning of the component with pressure, fuel and temperature environments.

4. Cyclic structural loads applied for two design lifetimes (80,000 equivalent hours) with pressure, fuel, and temperature exposures.

5. Inspections to evaluate the structural integrity of the component, and to assess the fuel sealing performance of the component when compared to the known performance of actual C-130 wing fuel tanks.

FUEL TANK TEST FACILITY

The prime consideration in the design of the WRDC fuel tank test facility, for use with the C-130 and other tests employing fuel, was safety. The use of actual aircraft fuel, either JP-4 or JP-5 made it mandatory to prevent accidents which could result in explosion or fire.

The test areas are enclosed on four sides with metal walls which have been sealed to contain any fuel spills. The enclosed test areas are vented to the outside with an exhaust duct system. All personnel entering the enclosure are required to wear non-static generating garments. No ignition sources are located within the enclosures. A remotely actuated fire extinguishing system is installed in each test enclosure.

SIMULANTS VERSUS ACTUAL FUEL

The use of simulants in place of actual jet fuel has numerous advantages, the most important of which is the safety aspect. Nonflammable simulants or those which are not easily ignitable would be preferred. The chemical effects upon the sealant systems being tested as a result of exposure to actual jet fuel is important. These effects can not be achieved by use of water based simulants or petroleum products such as Shell Pella-A.

Testing has shown that water-based glycerin solutions which match the surface tension values of jet fuels will not validate the leak integrity of aircraft integral fuel tanks (ref. 13). This is also true of the Shell Pella-A type of products. Pella-A oil is much more viscous than JP-4. It flows through capillary openings at a much slower rate than JP-4. Therfore, this hydrocarbon fluid is not a good simulant for fuel in leakage studies.

To reduce the volume of fuel contained in the fuel tank test componens, the tank interiors are partially filled with a light weight, non-absorbing, fuel resistant foam material. The foam displaces a large portion of the volume but still permits fuel to reach the entire interior surface. The material used is a polymethacrylic imide rigid expanded plastic. The brand name is ROHACEL. This material is resistant to JP-4, JP-5 and JP-8. It can be used at temperatures of more than 275°F.

HEATING/COOLING SYSTEM

Test requirements were a minimum temperature of 65°F, and a maximum of 160°F with fuel present in the test article. Two approaches were considered to meet these requirements. The first involved the heating and cooling of the structure by circulating pre-heated air over the structure. The cold temperatures were to be achieved by circulating cold nitrogen gas. The second method considered employed quartz infrared heating lamps and the circulation of cold nitrogen gas.

The second method was chosen as the easiest to carry out. This method also insures better control of the temperature distribution at the test article. The nitrogen gas cooling system could also be used during the heating cycles to insure an inert atmosphere, thus reducing the fire hazard.

An aluminum enclosure was constructed which contains the heating lamps and nitrogen gas manifolds. The enclosure was designed to fit around the test article with sufficient clearance at each end to allow for structural deflection during loading. The heating lamps are 1000 watts each and were wired to provide independently controlled heating zones. This was necessary to provide higher heat inputs at the ends of the test component where the load reaction and load introduction sections are located. The heating zones are controlled with a conventional thermocouple feedback system using commercial heat controllers and function generators. Redundant thermocouples are used along with a temperature alarm system to prevent over heating the structure. The cooling system employs pneumatically operated valves which regulate the flow of cold nitrogen gas to the spray bars located within the heating/cooling enclosure. The cold nitrogen is supplied from a 10,000 gallon liquid nitrogen dewar and heat exchanger system.

The oxygen level within the heating/cooling enclosure is monitored with remote sensors. Power to the heating lamps is never applied if the oxygen level is above 6%. The sensors provide a visual warning at 4% and a combined visual and audible alarm at 6% or above.

PRESSURIZATION SYSTEM

Fuel tank pressurization is with nitrogen gas controlled by a system of solenoid valves. The use of nitrogen gas eliminates the possibility of an explosive mixture forming in the tank. Test article safety is achieved through a redundant over pressure protection system employing pressure sensors and pressure relief solenoid valves.

LOAD APPLICATION METHODS AND SAFETY

The test fixture for the C-130 wing tank component interfaces with the load reaction section at the inboard end of the component. The component is mounted as a cantilevered beam with three pin-pin connections and one pin-fixed connection. The six active loads are applied using hydraulic cylinders controlled through a servo hydraulic feedback loop. Load feedback is obtained from six strain gage based load cells, one attached to each load application hydraulic cylinder. Each load cell has three measurement circuits. One is used as the feedback element of the servo controlled loop, the second is employed in a redundant overload protection system, and the third is used in the data acquisition and load monitoring system.

CONCLUSIONS AND RECOMMENDATIONS

The results obtained form the coupon level testing have shown that the approach used to develop the loads and environmental spectra are valid. The durability spectra coupons showed the fuel tank certification loads spectra did simulate the fatigue and fracture aspects of the baseline spectra. The coupon test results agreed with the analytical predictions made when the certification spectra were generated.

The environmental exposure spectra were also certified through successful coupon testing. The results of the five different coupon tests all verified that the assumptions made were correct or there was litte effect.

Testing of the first C-130 fuel tank test component has been completed. The goal of accumulating 80,000 equivalent flight hours (two aircraft lifetimes) was not achieved due to fatigue failures which became impractical to repair. Testing was terminated after approximately 60,000 flight hours. The fatigue failures which occurred through out the test were carefully documented and repairs designed and installed. It should be emphasized that these failures cannot be correlated to actual in service C-130 aircraft due to the design of the test component and the loading methods employed. The failures were typical sometimes in that they occurred in lower wing skin riser run out areas as seen in actual C-130's.

Testing of the second C-130 test component is in progress. The time required to reach 60,000 flight hours, allowing for fatigue repairs and inspections is approximately nine months. Testing has yet to be completed and results are not available at this report time.

The methods developed have been employed in other fuel tank sealing certification programs conducted by WRDC in support of industry research and development programs. The environmental spectra developed for fighter wing and fuselage tanks have proven to be very effective at uncovering fuel sealing system problems in short time periods. The fighter wing tank environmental spectra has been used extensively. It is possible to apply the equivalent of 16,000 flight hours (two aircraft lifetimes) of combined structural and environmental exposure in 760 hours of testing time.

It remains to be seen, after completion of the full-scale C-130 component testing, if this approach will be imposed on future aircraft development efforts. Considerations which must be resolved include:

1. Safety of personnel, facilities and equipment when using actual fuel and high temperatures.

2. The size of the test component may be a problem. Should the entire aircraft, the entire tank only, or a preliminary design verifiction component be used?

3. The size of the component can be directly proportional to the length of the test and the costs involved. Should fuel leaks become a problem during testing, more time could be spent finding fuel leaks than testing, especially if a new sealing system is being evaluated.

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RECORDER'S REPORT OF FINAL DISCUSSION

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The concluding session of the workshop was devoted to a discussion by the participants. The results of this open forum have been summarized along with specific subjects where it was felt that further work was necessary. Participation in the discussion was vigorous, with many of the attendees agreeing on common problem areas.

Current technology concerning structural design to ensure leak free fuel tanks is essentially unchanged from that of 20 years ago. Traditionally, aircraft integral fuel tanks have been designed from a structural viewpoint first and as a fuel tank last. New sealants and fasteners have been developed, but little work has been performed to evaluate fastener/sealant systems for leak susceptibility. The increased application of composite materials has also led to fuel sealing problems.

One area of concern is the increased application of composite and fiber reinforced plastics (CFRP) in structures which must be sealed for fuel tank use. These structures must be designed with a minimum need for interior access. The use of blind fasteners and gap filling materials should be avoided in CFRP fuel tank designs. The removal of sealant from CFRP structures often damages the structure itself. Removal methods which are not damaging to the laminates are often damaging to the subsystems within the integral tanks. Improvements in sealants, such as easier removal, is a possible solution to these problems. Sealant primers designed for CFRP materials and sealants with lower adherence and higher coherence offer possible solutions.

Several design considerations were discussed which apply to conventional as well as CFRP structures. The number of penetrations into and through an integral fuel tank must be minimized. These penetrations include fasteners and subsystems. Fuel tanks should be designed for minimum access to accomplish inspections and repairs. The use of external repair methods, such as injection groove sealing, whenever possible, is recommended. Careful attention must be given to the design of the tank structure to eliminate areas which are difficult to access, both during fabrication and while in service, for sealing and inspection. Experience has shown that the presence of fuel in a structure, when combined with aircraft flight loads and vibrations, can result in unexpected structural cracking. Structural designers should take such combined environments into consideration.

Sealant application methods require improvement for production environments. Although it is desirable to have a well trained and experienced work force, this is not always accomplished. Sealants which can be easily applied and are tolerant of time and temperature conditions in the work environment are needed. Longer cure times would permit the inspection and correction of problems in the assembly of larger parts.

Field repair of leaks is a continual problem. Many of the specialized equipment items used for repair are not compatible with existing NATO aircraft shelters. Problems with the removal of toxic and flammable vapors and static grounding are common. Sealants are needed which are tolerant to contamination of repair areas and will cure over a wide range of temperatures in shorter time. Consideration must be given for the use of repair materials in a flight line environment. Improvements in training manuals and the possible use of video training methods should be considered. Concerns were expressed about the problems of inspecting fuel tanks for structural damage due to the presence of sealants covering the inspection areas.

It was felt that many existing leak problems could have been avoided if structural testing to certify fuel tank leak integrity had been performed early in the development phase of the aircraft design. The testing of aircraft fuel tanks has in the past been limited and usually involved the simple pressurization of the structure while filled with water or other simulants. Such testing has proven to be wholly inadequate as evidenced by the many leak problems which have occurred in service. Fuel tank testing must be accomplished using realistic combinations of both flight loading and other environmental factors such as temperature, humidity, and pressure. The aging of the sealant systems as a result of chemical interaction with hydrocarbon fuels must be duplicated during testing to provide valid performance information during the expected service life of the fuel tank. This aging can only be accomplished by combining environmental exposures with the use of actual fuel in the test structure.

Areas of further research recommended by the attendees were:

A. Materials
1. Primer systems for CFRP systems.
2. Sealants which are easier to remove from CFRP structures, higher coherence, lower adherence.
3. Sealants with higher temperature capabilities.
4. Sealant specifically designed for rapid repair situations; tolerant to contaminated surfaces, short cure times and suitable for field storage and application.
5. Sealant systems which can be applied using spray technology.

B. Design & Certification
1. Sealing concepts which are integrated into the design process.
2. CFRP detail design improvements with emphasis on tank access, minimization of joints and fasteners.
3. Inclusion of the vibration environment in the design process with emphasis on fluid structure interaction, aero-acoustic and temperature effects.
4. Improved testing mehtods which include the chemical aging effects of the sealing systems and uncover potential problems early in the aircraft development.

C. Maincenance
1. Improved manuals and training.
2. Improved leak source location procedures which require minimal interior access and can be used in the field.
3. Sealant removal techniques which do not result in damage to non-metallic integral fuel tank structures.
4. Fuel tank repair equipment and procedures which can be used in NATO standard aircraft shelters without compromising personnel and aircraft safety.

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14. Abstract

At its sixty-eighth meeting, the Structures and Materials Panel held a Workshop to exchange experiences and information concerning aircraft fuel tank technology, to exchange information concerning current design practices and discuss detection and repair of fuel leaks and modification practices to improve fuel tank integrity.

The Workshop provided a very useful forum for the exchange of information which is reflected in the papers presented and the summary of the discussions contained in this report.

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